Perspectives on Baryon Number Violation

David McKeen TRIUMF

TIFERBNV, Part 1 Aug. 6, 2020
(Formerly ACFI Workshop, now Snowmass on the web)

Why is the proton long-lived?

In the EFT describing hadrons, can have

$\mathcal{L}_{eff} \supset \lambda \pi^0 \overline{e^c} p + h.c. \Rightarrow$ 

, $\tau_p \simeq \frac{16\pi}{\lambda^2 m_p}$

Empirically $\tau_p \gtrsim 10^{34}\,yr \Rightarrow \lambda \lesssim 10^{-32}$ Why?

(Zee '08) Fundamental th'y involves quarks

$\Rightarrow$ Baryon # accidentally conserved (@ dim-4)

$\mathcal{L} \supset \frac{1}{\Lambda^2} \overline{e^c} u \overline{u^c} d + h.c. \Rightarrow \frac{m_p^2}{4\pi\Lambda^2} \pi^0 \overline{e^c} p + h.c.$

$\Lambda \gtrsim 10^{16}\,GeV$

In the SM, Gauge Inv (at dim-4) $\Rightarrow$ $\left\{ \begin{array}{l} q \text{ couple to } q \\ \ell \quad \text{"} \quad \text{"} \; \ell \end{array} \right\}$

$\Downarrow$

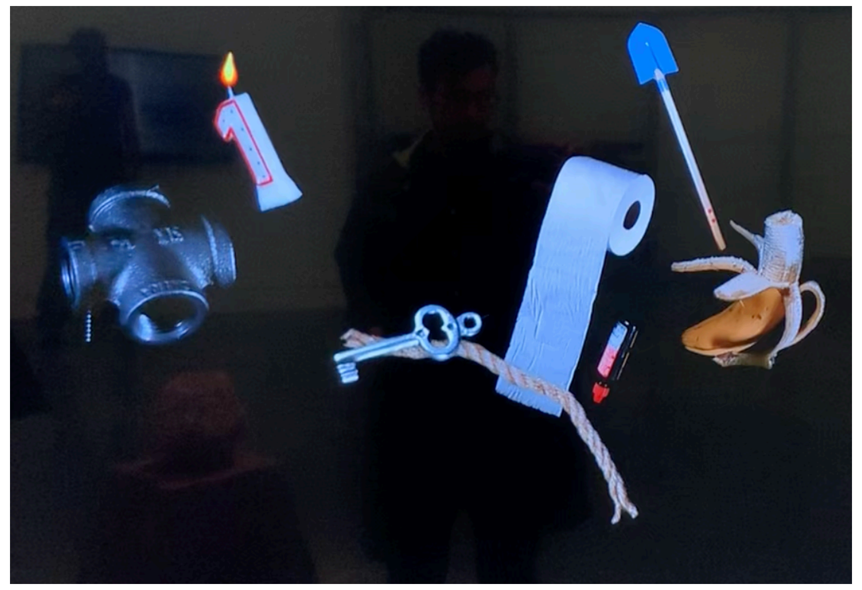
B & L conserved!

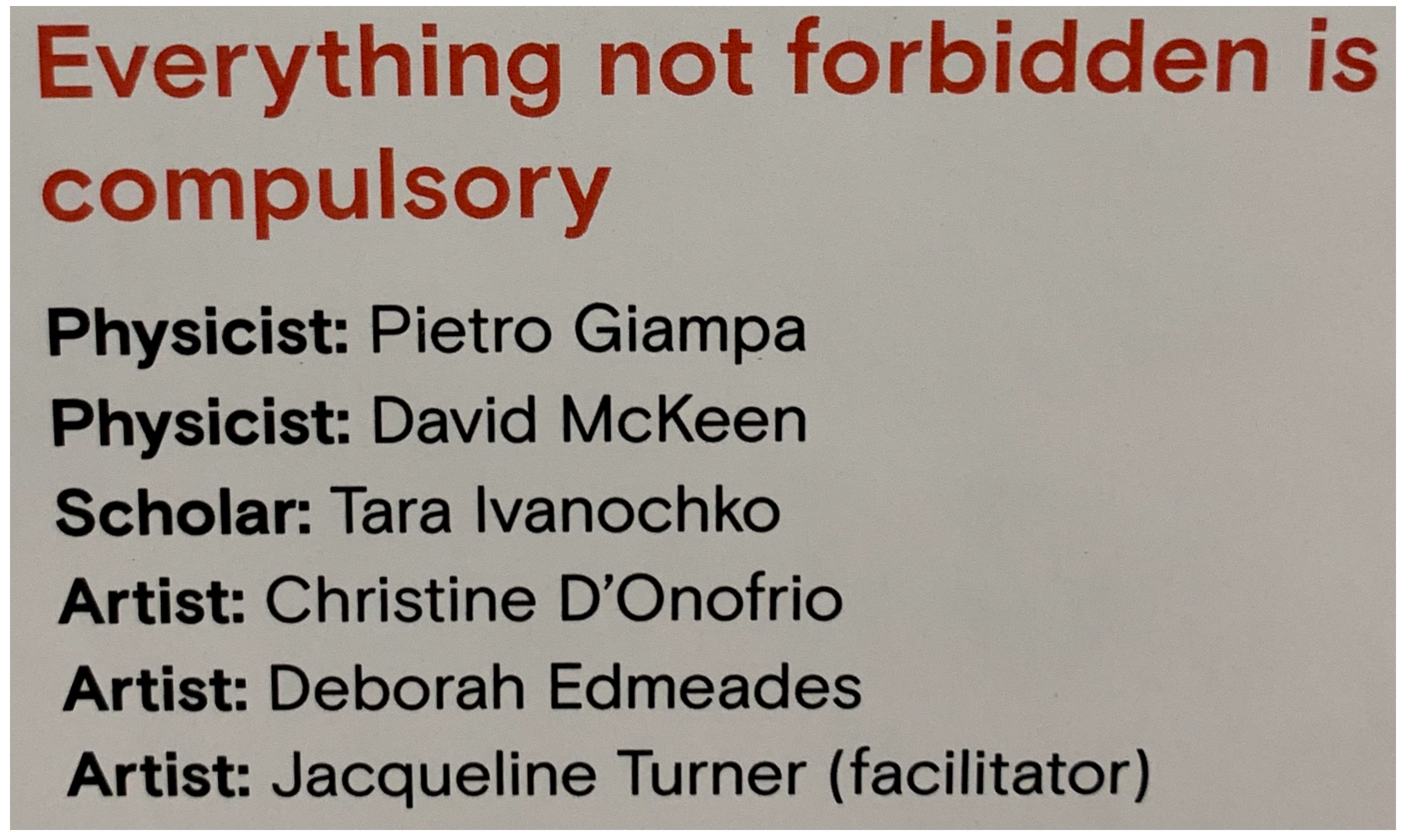
HOWEVER:

($\cancel{B}$, $\cancel{L}$) non-pert. (B−L conserved)

Universe not $B-\bar{B}$ symmetric

ν masses req. new DOF, e.g. N and must have $\mathcal{L} \supset M \bar{N}^c N$




Everything not forbidden is compulsory

Physicist: Pietro Giampa
Physicist: David McKeen
Scholar: Tara Ivanochko
Artist: Christine D'Onofrio
Artist: Deborah Edmeades
Artist: Jacqueline Turner (facilitator)

$\Delta B = 1$ vs. $\Delta B = 2$ observables

p decay probes scales $\Lambda \sim 10^{16}$ GeV
well motivated by GUTs

$\Delta B = 2$? $\mathcal{L} \supset \frac{(udd)^2}{\Lambda^5} \longrightarrow \mathcal{L}_{eff} \supset \frac{m_n^6}{(4\pi)^4 \Lambda^5} \overline{n^c} n \equiv \frac{\overline{n^c} n}{\tau_{n\bar{n}}}$

(Marshak, Mohapatra, ...)

(see talk by Wagman)

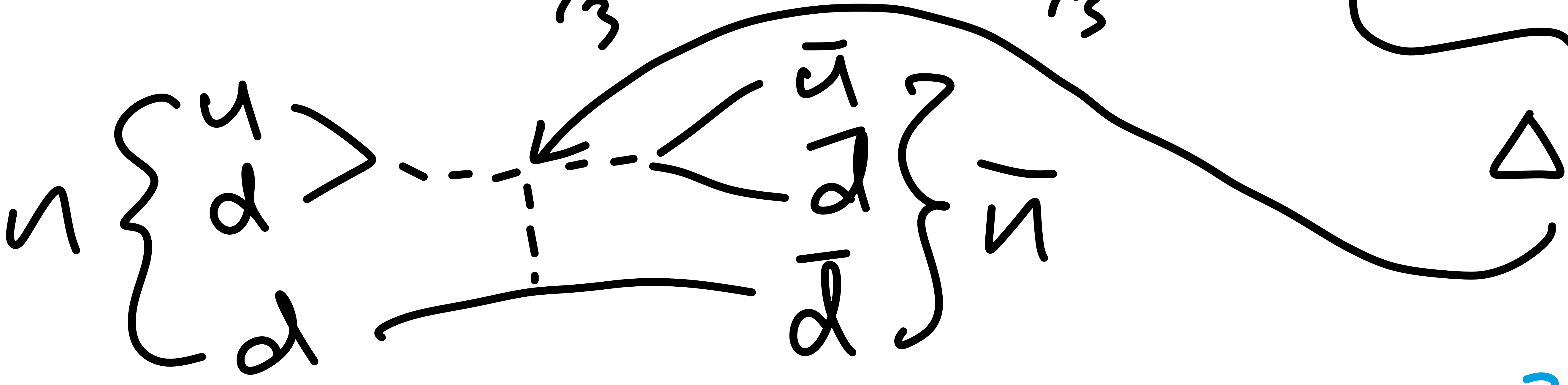
$\tau_{n\bar{n}} \gtrsim 10^8$ s $\Rightarrow \Lambda \gtrsim 100$ TeV much lower than p...

BUT this naive expectation may not be true!

For example...

$$\mathcal{L} \supset \lambda X_{-1/3}\, ud + \lambda' X_{2/3}\, dd + \underbrace{\mu X_{-1/3} X_{-1/3} X_{2/3}}_{\Delta B = 2}$$

(Arnold, Fornal, Wise '13)
(further discuss. see Gardner)



relate B & L

Also L-R models [w/ $U(1)_{B-L}$] $\left(Q = T^3_L + T^3_R + \frac{B-L}{2}\right)$

ν masses ⇒ only seen $\Delta L = 2$ ⇒ only $\Delta B = 2$?

[connected to cons. of B-L in SM]

see talk by Mohapatra

See also "mirror world shortcut": Berezhiani

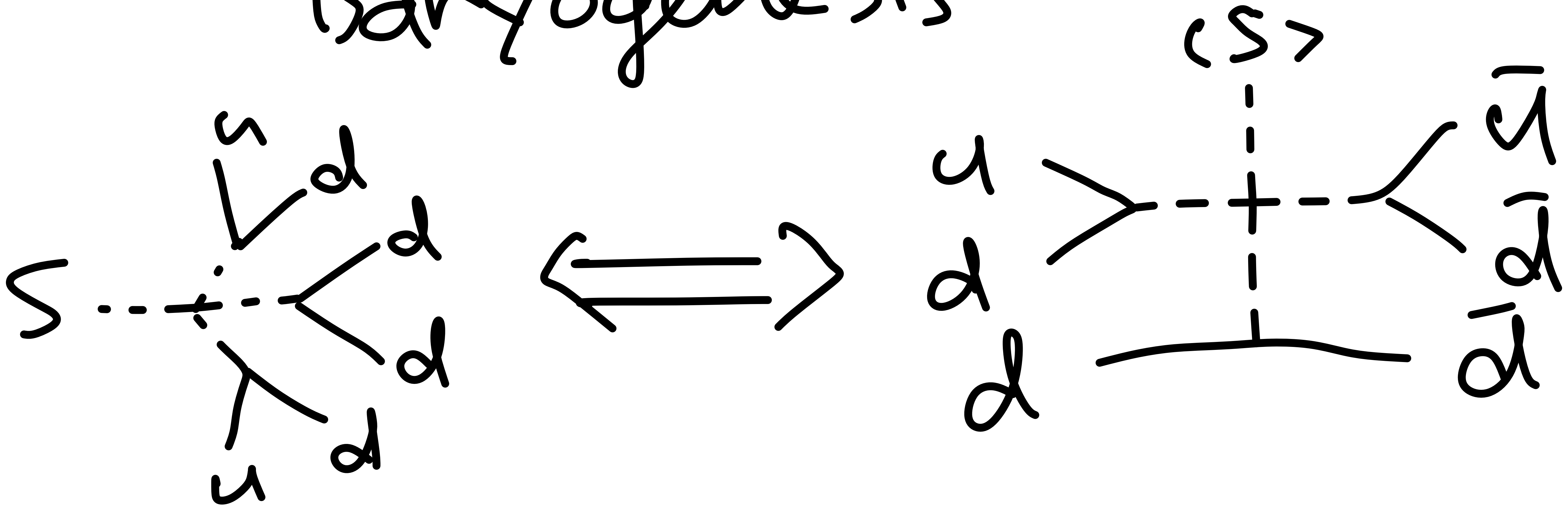
and extra-dim thys: Shrock

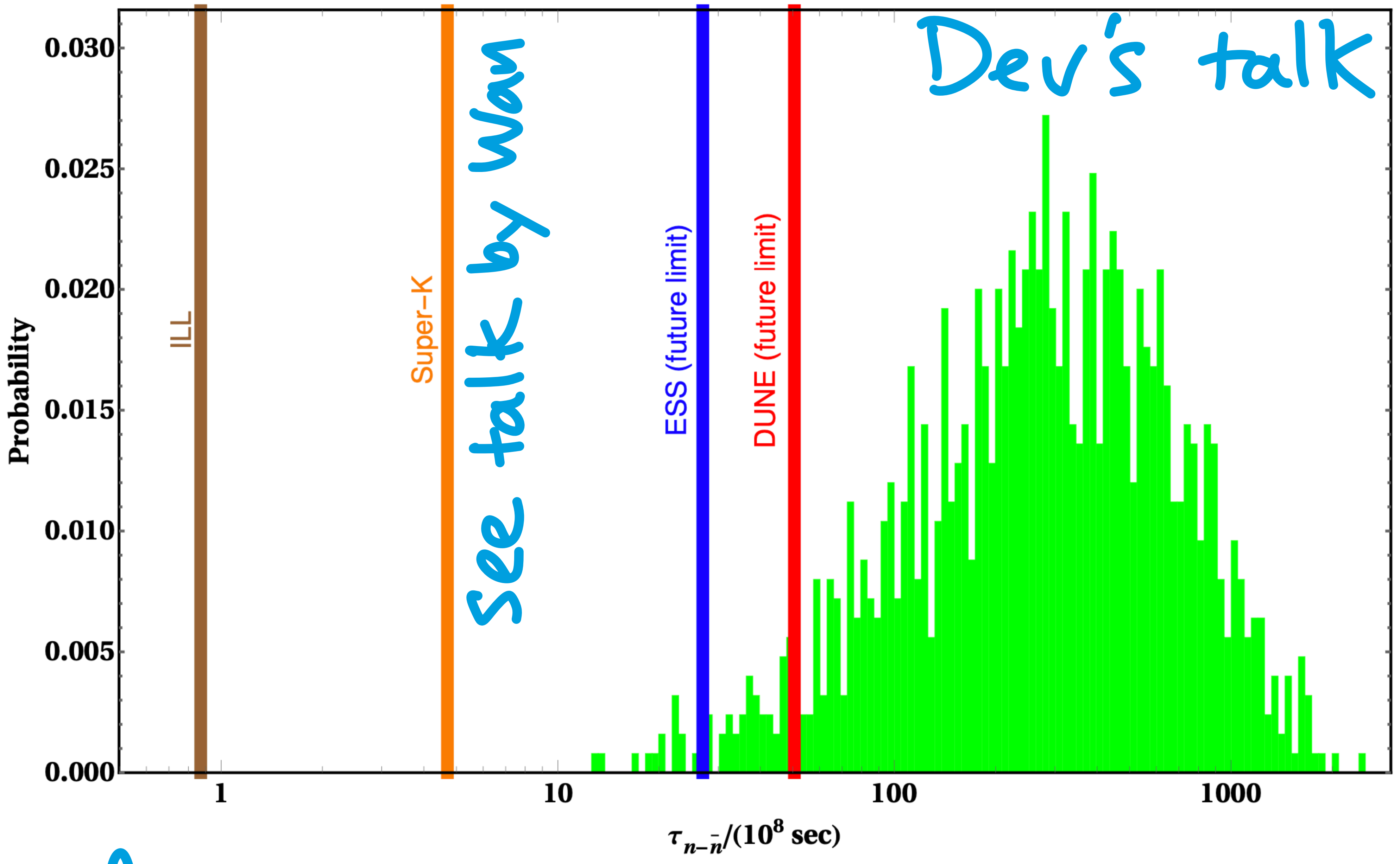
(Other values of $\Delta B, L$ in talk by Heeck)

$\Delta B = 2$ and Baryogenesis

Models w/ "large" $\Delta B=2$ are useful

e.g. Post Sphaleron Baryogenesis (Babu, Dev, Mohapatra, ...)





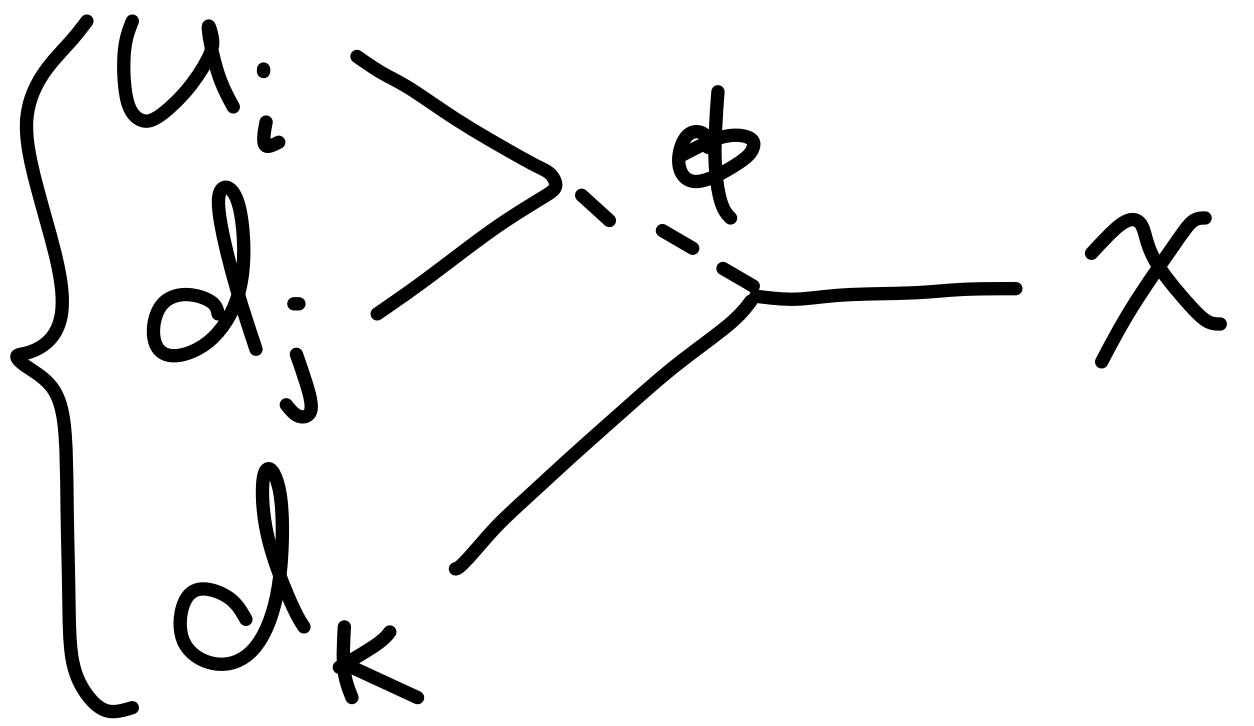
can be intimately related to ν masses (see talks by Babu, Mohapatra)

Heavy Baryon Baryogenesis

(DM & Nelson)

$$\mathcal{L} \supset -g_{ij}\,\phi\, u_i^c d_j^c - y_k\, \phi^* d_k^c \chi - m_\chi^{\Delta B=2} \chi\chi + h.c.$$

Heavy flavor baryon



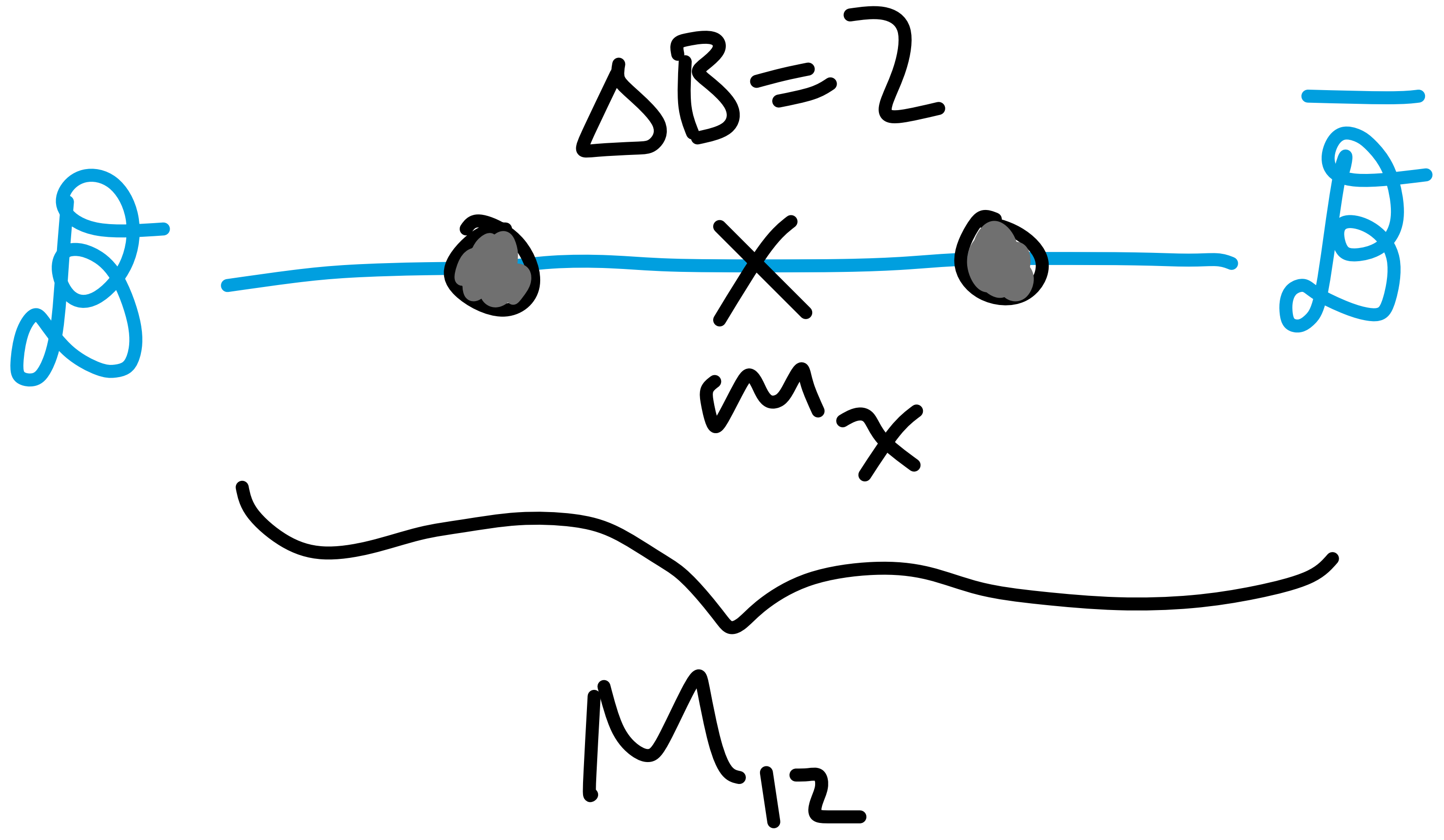
$$\mathcal{L}_{eff} \supset \underbrace{\frac{g_{ij} y_k}{m_\phi^2}}_{1/\Lambda^2} \underbrace{u_i^c d_j^c d_k^c}_{\to \bar{B}} \chi + h.c.$$

$m_\chi \sim \mathcal{O}(\text{GeV})$ is interesting ("dark baryon")

p & ^{9}Be stability requires (Pfützner & Riisager)
$m_\chi > 938.0$ MeV

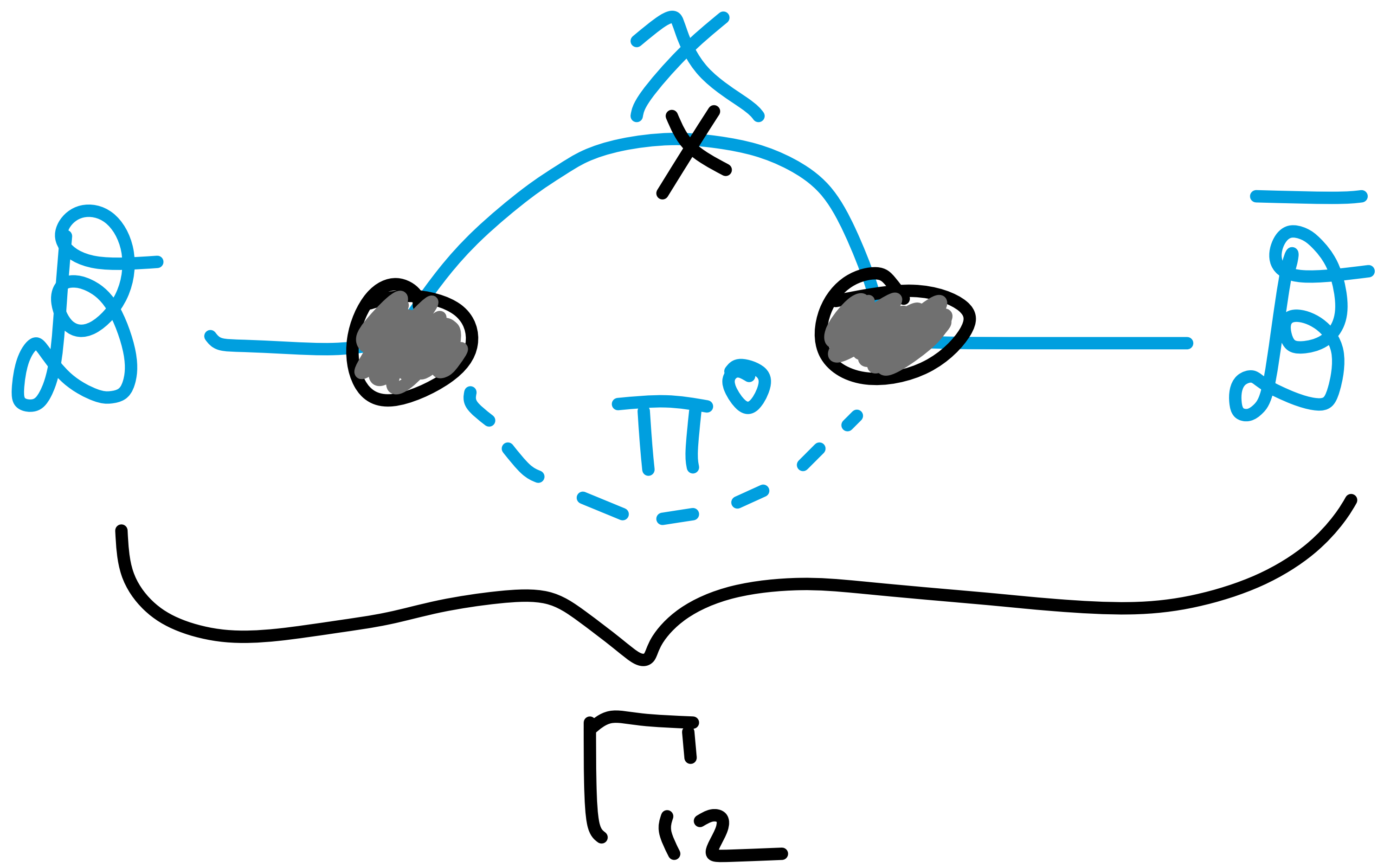
[connection to mirror world? talks by: Berezhiani, Kamyshkov, Young]

Heavy flavor baryon oscillations: $\cancel{CP}$



$M_{12} \propto \frac{1}{\Lambda^4}$ can be "big" $\Lambda \sim$ TeV (Kuzmin)

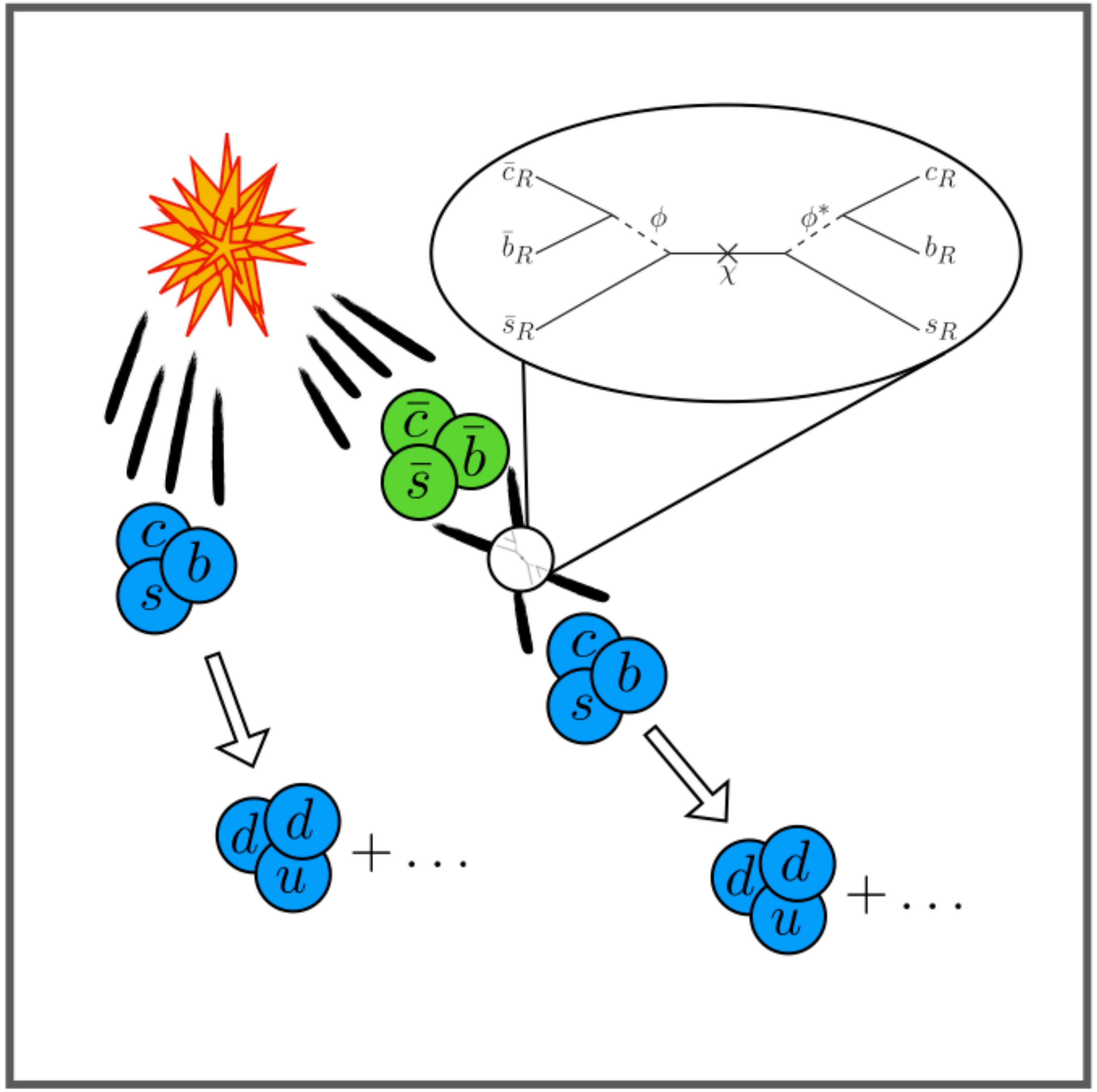
No dinucleon decay for, e.g. $\Delta s = 4$



$\Delta m \sim \mathcal{O}(100\,\text{MeV}) \Rightarrow \left|\frac{\Gamma_{12}}{M_{12}}\right|$ not small

Is this useful?

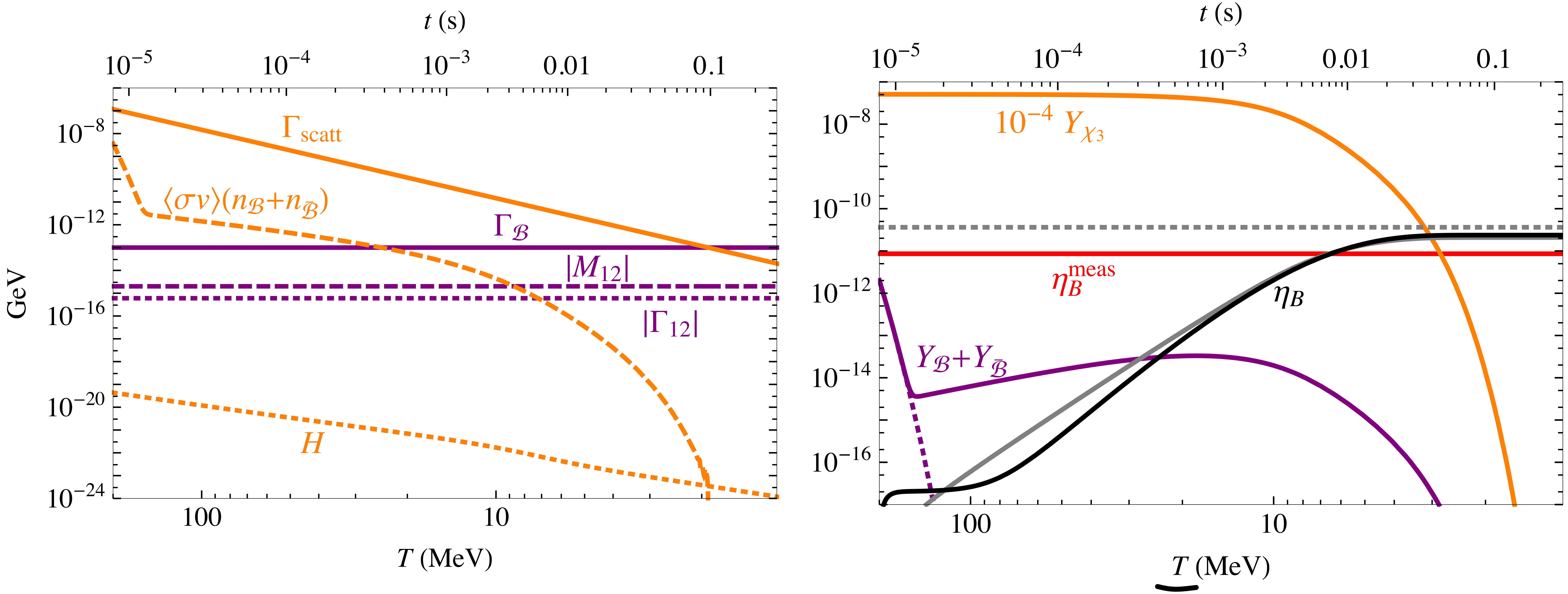
Heavy flavor baryon oscillations: Baryogenesis



Produce heavy baryons out of eq. (e.g. inflaton decay), CPV & $\Delta B = 2$ biases decays to B

Similar to B-meson oscillation baryogenesis (Alonso-Alvarez, Elor, Escudero, Nelson)

Heavy flavor baryon oscillations: Baryogenesis



Decoherence important
$\Rightarrow$ action is ~ 10 MeV

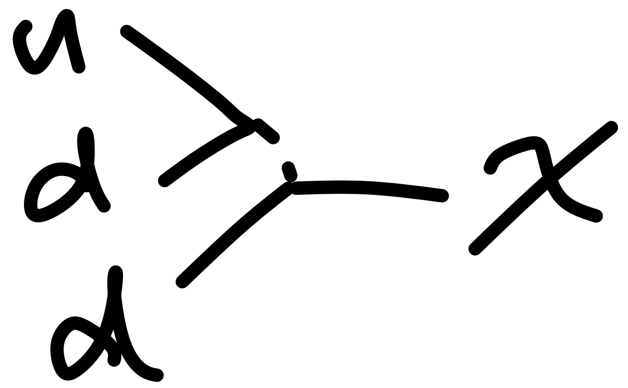
$\Omega_{cb}-\bar{\Omega}_{cb}$ system

$$m_{\mathcal{B}} = 7\ \text{GeV},\ \Gamma_{\mathcal{B}} = 3\times10^{-12}\ \text{GeV}$$
$$|M_{12}| = 3\times10^{-15}\ \text{GeV},\ |\Gamma_{12}/M_{12}| = 0.3$$
$$m_{\chi_3} = 7.5\ \text{GeV},\ \Gamma_{\chi_3} = 3\times10^{-23}\ \text{GeV}$$

What about Dirac Dark Baryons?

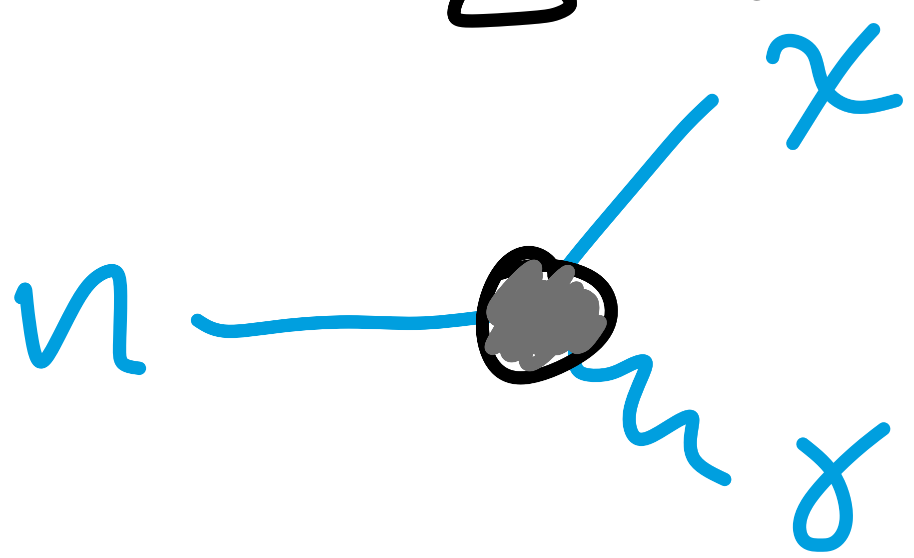
Low energy theory is

$$-\mathcal{L} \supset m_n \bar{n} n + m_\chi \bar{\chi}\chi + \delta(\bar{n}\chi + \bar{\chi} n)$$



No longer strong $n \to \bar{n}$, $nn \to \pi\pi$ bounds

$\theta = \frac{\delta}{\Delta m}$ can be much bigger. Useful?



$$Br_{n\to\chi\gamma} = 1\% \left(\frac{\theta}{5\times 10^{-10}}\right)^2 \left(\frac{\Delta m}{MeV}\right)^3$$

[direct search @ LANL]

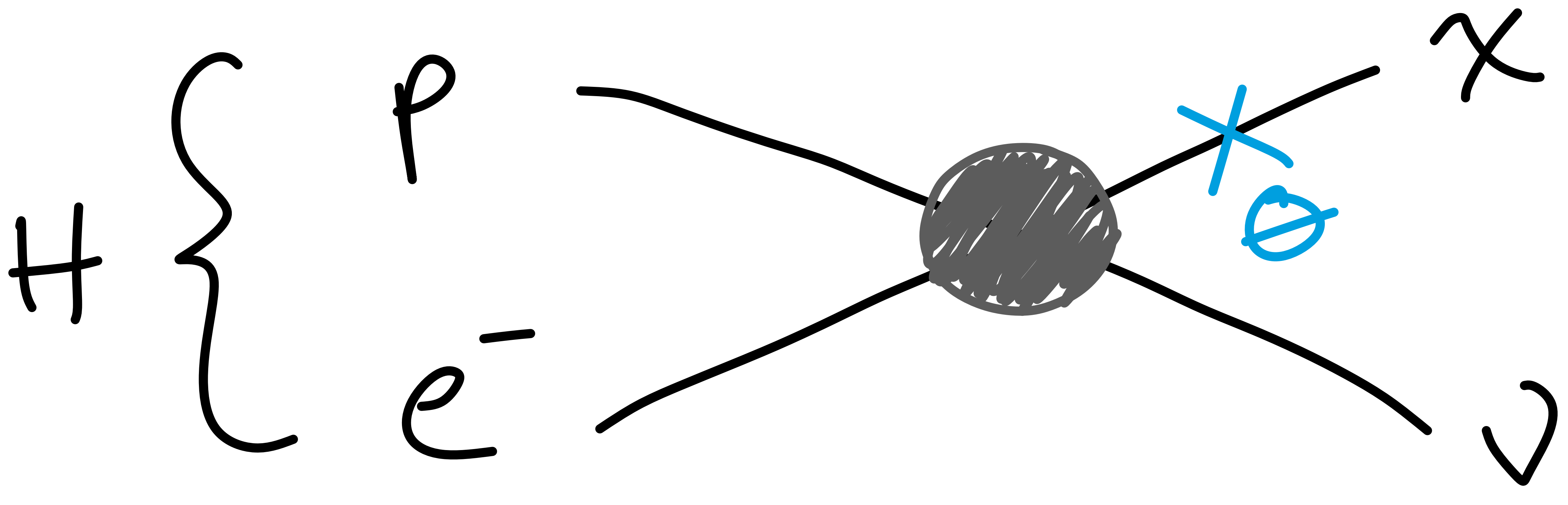
n lifetime anomaly, χ as DM (stable if $m_\chi < m_e + m_p$)

(Fornal, Grinstein, Berezhiani, Cline, Cornell, ...)

Where else??

Atomic Hydrogen decay

If $m_\chi < m_p + m_e = m_H$ (+13.6eV), i.e. where χ is stable

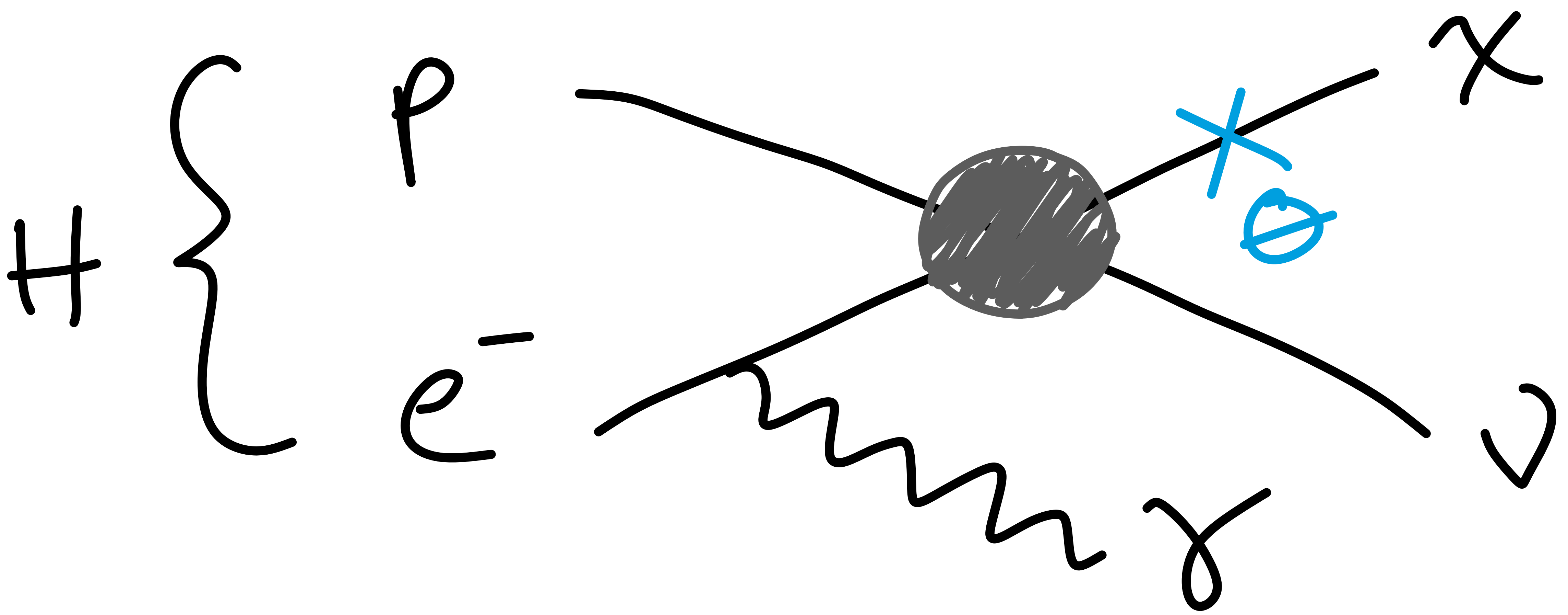


Leading mode

$$\tau_H \sim 10^{27}\,s \left(\frac{10^{-9}}{\Theta}\right)^2 \left(\frac{m_e}{Q}\right)^2$$

Invisible - hard to test...

and...



$$Br_\gamma = \underbrace{\frac{\alpha}{12\pi}}_{2\times 10^{-4}} \left(\frac{Q}{m_e}\right)^2$$

Berezhiani; DM & Pospelov

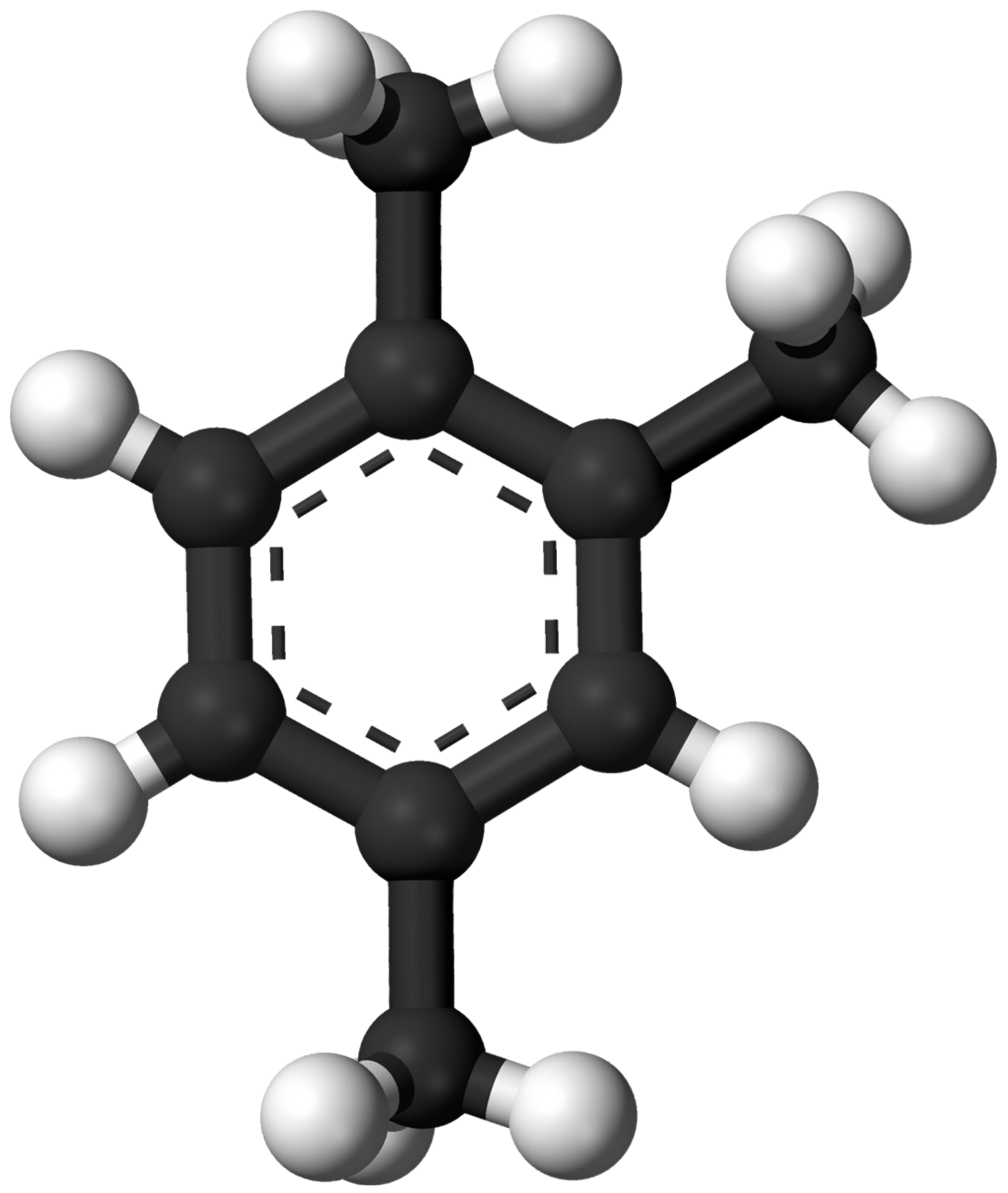
Need: lots of H

sensitivity to $\mathcal{O}$(100 keV γs)

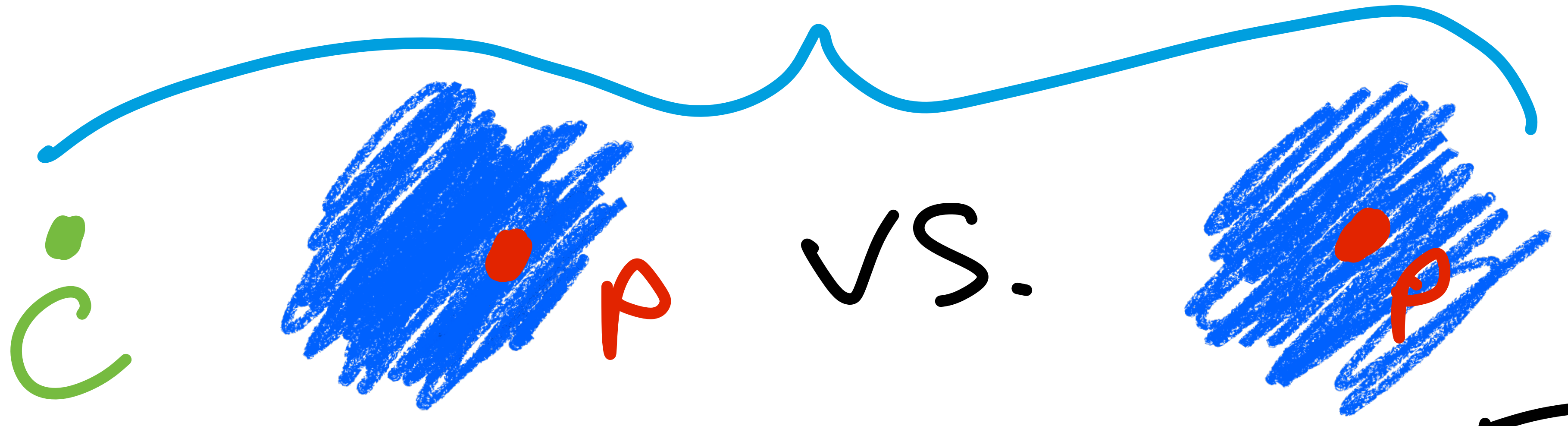
e.g. Borexino

$\mathcal{O}$(100 t) pseudocumene

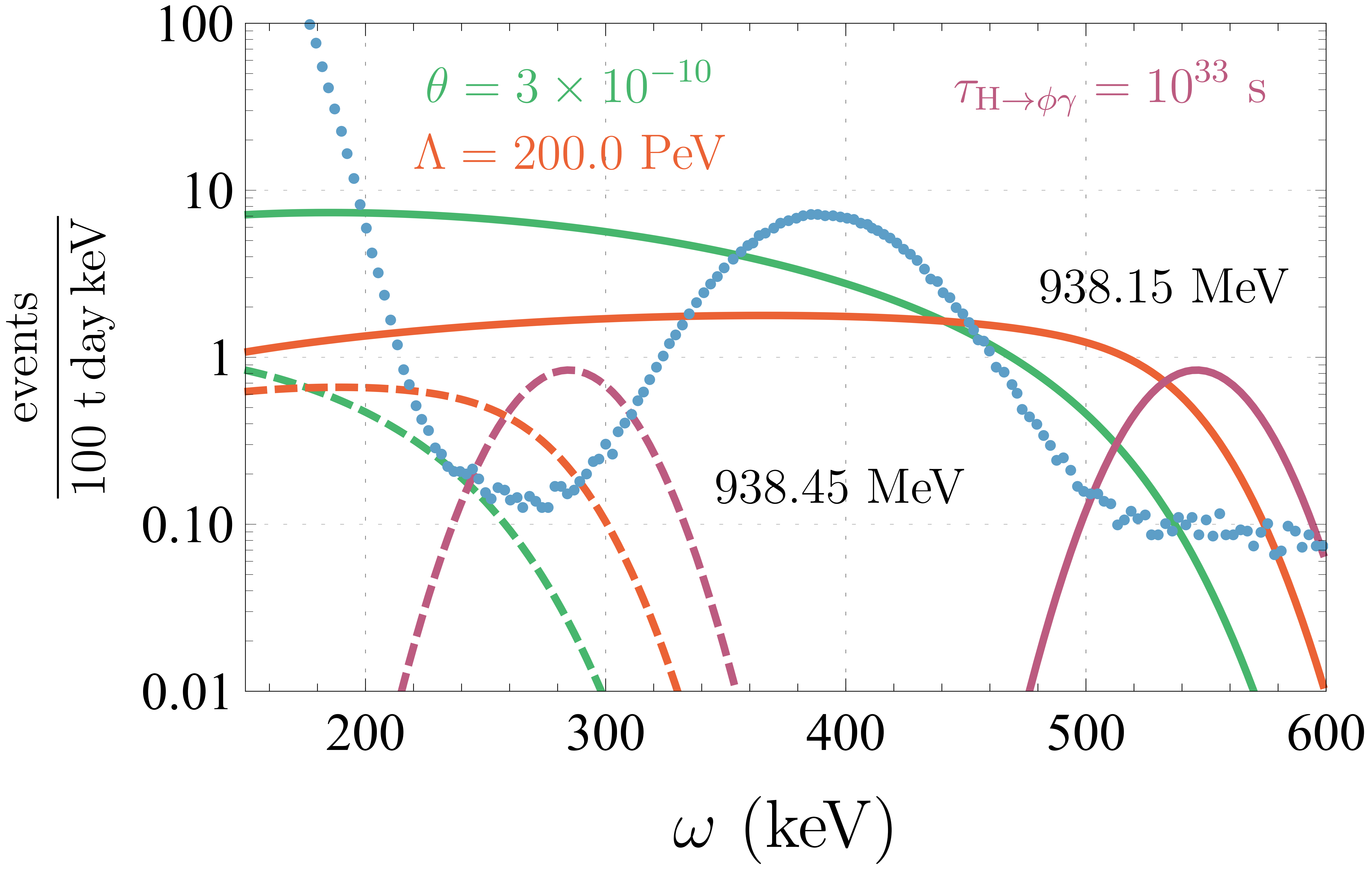
$C_6H_3(CH_3)_3$ – 10% H



$$\text{Rate}: \frac{4\times10^4}{100\text{ t day}}\left(\frac{\theta}{10^{-9}}\right)^2\left(\frac{Q}{m_e}\right)^4\left(\frac{|\psi_{mol}(0)/\psi_H(0)|^2}{0.5}\right)$$



Spectrum @ BOREXINO



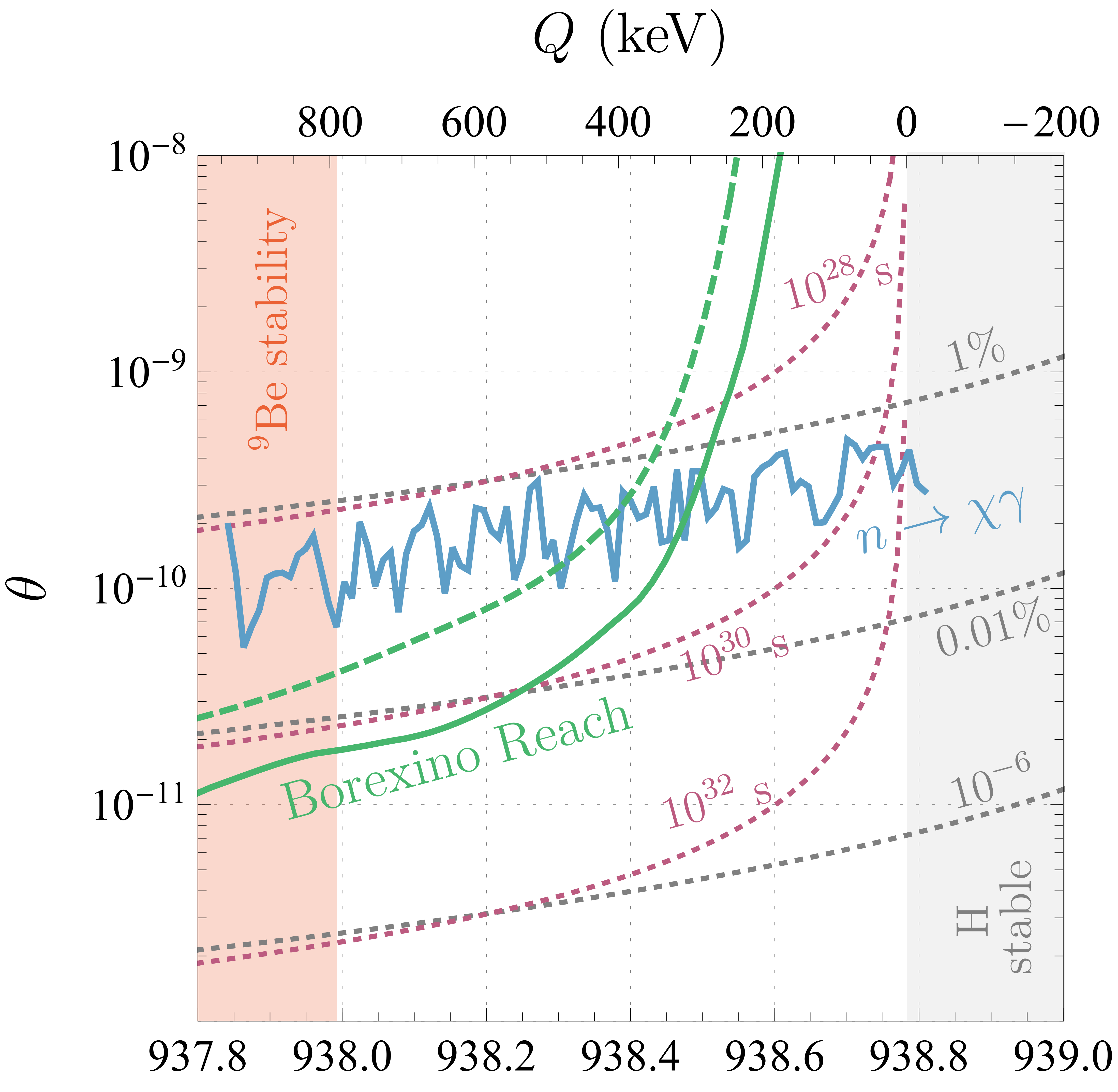
Blue: data from 1509.01223 (search for $e^- \to \gamma\nu$, test of Q cons.)

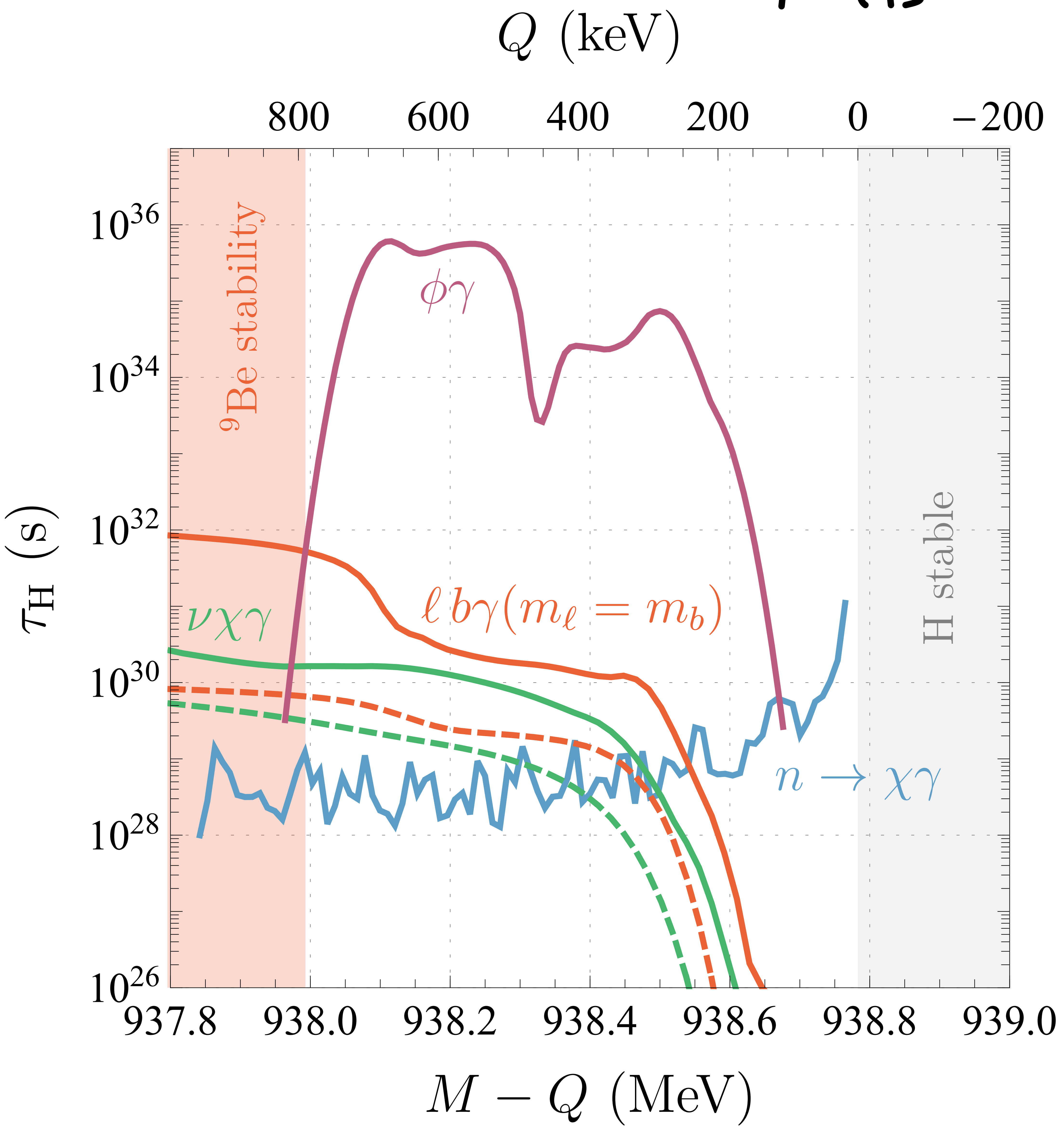
Green: $\chi \xrightarrow{\theta} n$

Purple: $\mathcal{L} \supset y \bar{e}^c p \phi$

Red: $\mathcal{L} \supset \frac{1}{\Lambda^2} \bar{\chi} e \bar{b} p$

Fit Results - can probe $\tau_H \sim 10^{30}$s in this model





DM & Pospelov

Wrap Up

Baryon # accidentally conserved in SM (@T=0)

$\Delta B = 1$ (proton decay) can probe $\not{B}$ at very high scale but $\Delta B = 2$ ($n \to \bar{n}$, $NN \to \pi\pi$, ...) can be leading effect & directly related to B.A.U.

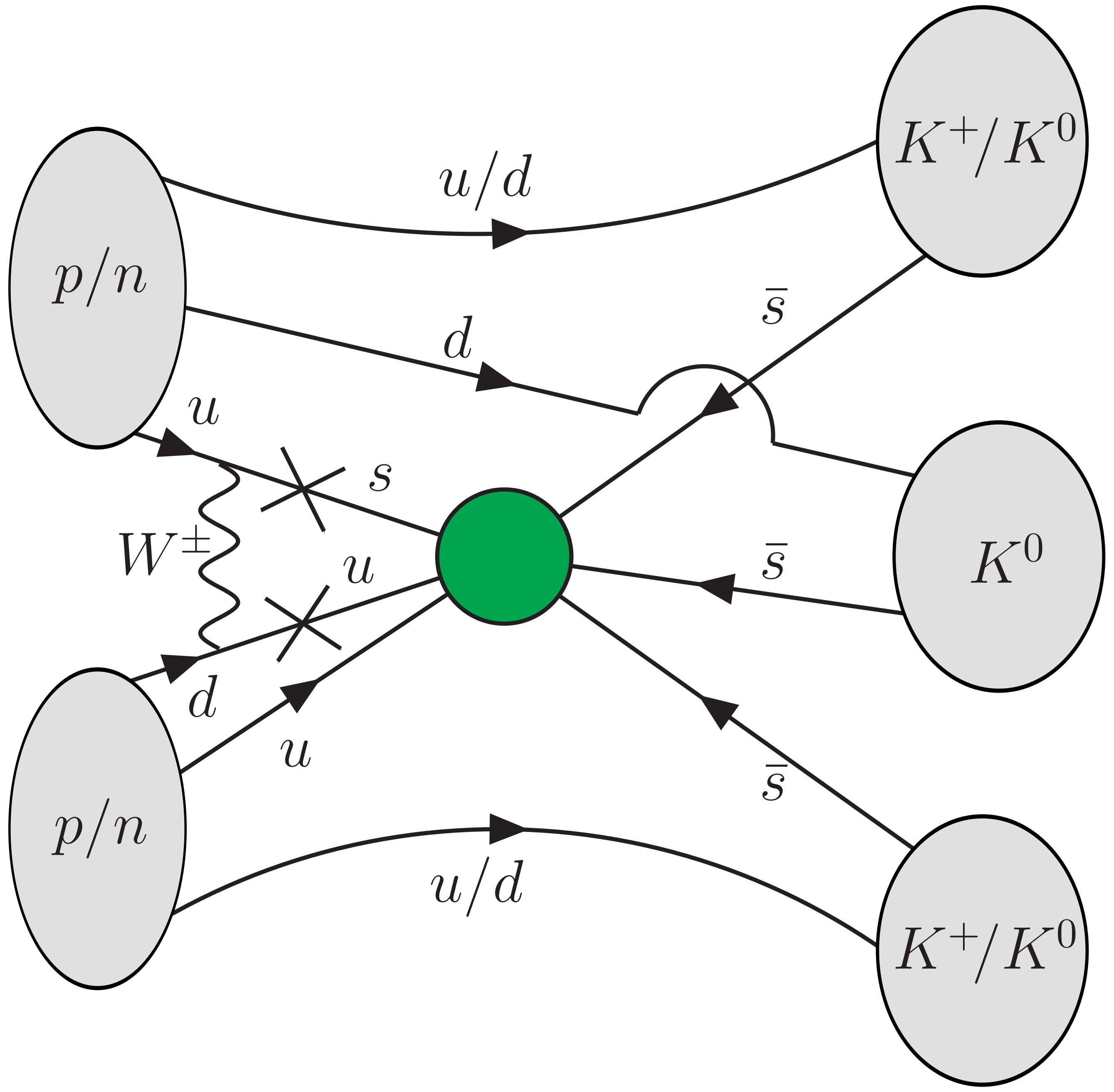
Models where Baryon # leaks into "dark sector" also well motivated & have novel signatures

Without more direct clues we need to cast a wide net & work across fields: theory/experiment, particle/nuclear/lattice, ...

Backup

Backup: (Indirect) Dinucleon Decay

There is still contribution to dinucleon decay in presence of weak interactions

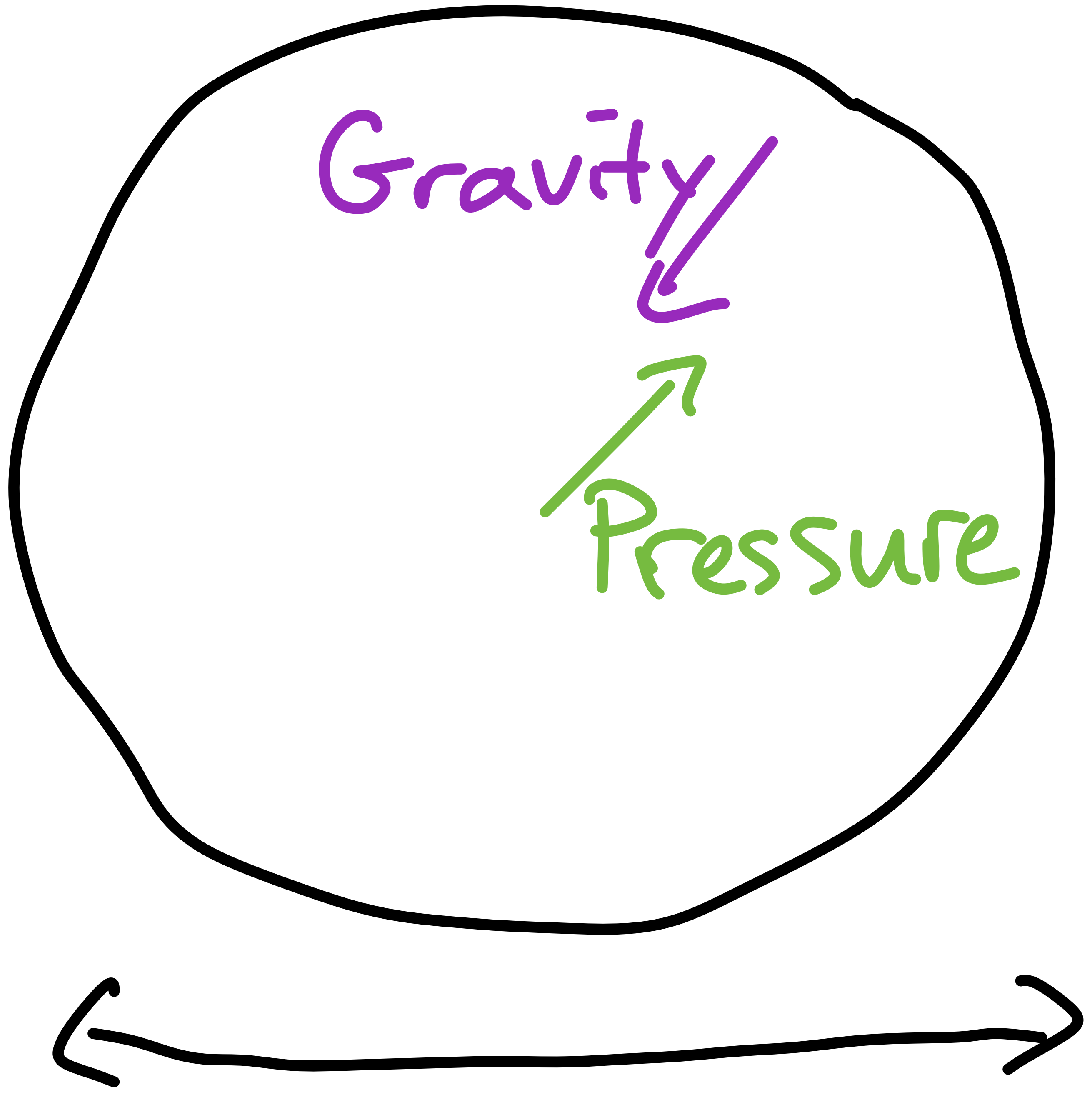


Operator	$\mathcal{B}$	Weak Insertions Required	Measured Γ (GeV) [19]	Limits on $\delta_{\mathcal{BB}} = M_{12}$ (GeV) Dinucleon decay	Collider
$(udd)^2$	n	None	$(7.477 \pm 0.009) \times 10^{-28}$	10^{-33}	10^{-17}
$(uds)^2$	Λ	None	$(2.501 \pm 0.019) \times 10^{-15}$	10^{-30}	10^{-17}
$(uds)^2$	Σ^0	None	$(8.9 \pm 0.8) \times 10^{-6}$	10^{-30}	10^{-17}
$(uss)^2$	Ξ^0	One	$(2.27 \pm 0.07) \times 10^{-15}$	10^{-22}	10^{-17}
$(ddc)^2$	Σ_c^0	Two	$(1.83^{+0.11}_{-0.19}) \times 10^{-3}$	10^{-17}	10^{-16}
$(dsc)^2$	Ξ_c^0	Two	$(5.87^{+0.58}_{-0.61}) \times 10^{-12}$	10^{-16}	10^{-15}
$(ssc)^2$	Ω_c^0	Two	$(9.5 \pm 1.2) \times 10^{-12}$	10^{-14}	10^{-15}
$(udb)^2$	Λ_b^0	Two	$(4.490 \pm 0.031) \times 10^{-13}$	10^{-13}	10^{-17}
$(udb)^2$	Σ_b^{0*}	Two	$\sim 10^{-3*}$	10^{-13}	10^{-17}
$(usb)^2$	Ξ_b^0	Two	$(4.496 \pm 0.095) \times 10^{-13}$	10^{-10}	10^{-17}
$(dcb)^2$	${\Xi_{cb}^0}^\dagger$	Two	$\sim 10^{-12\dagger}$	10^{-17}	10^{-15}
$(scb)^2$	${\Omega_{cb}^0}^\dagger$	Two	$\sim 10^{-12\dagger}$	10^{-14}	10^{-15}
$(ubb)^2$	${\Xi_{bb}^0}^\ddagger$	Four	$\sim 10^{-13\ddagger}$	>1	10^{-17}
$(cbb)^2$	${\Omega_{cbb}^0}^\dagger$	Four	$\sim 10^{-12\dagger}$	>1	10^{-15}

Naive estimate of suppression (proper treatment involves matching onto chiral perturbation theory)

$$\frac{1}{4\pi^2}\frac{G_F}{\sqrt{2}}|V_{us}^*|\,|V_{ud}|\,m_u m_s \log\left(\frac{m_W^2}{\Lambda_{\rm IR}^2}\right) \sim 10^{-10}$$

Neutron Stars

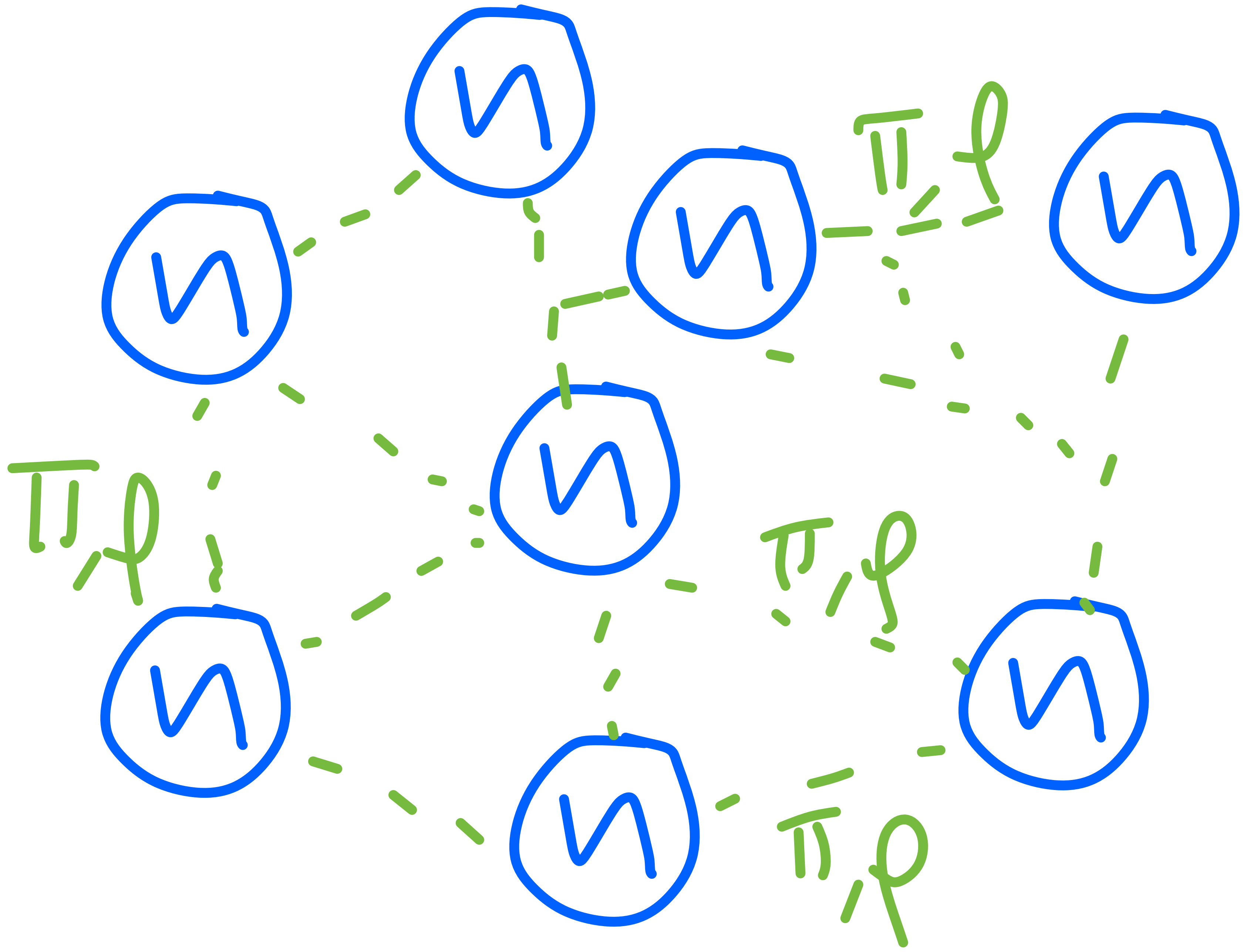


$\mathcal{O}(20\,\mathrm{km})$

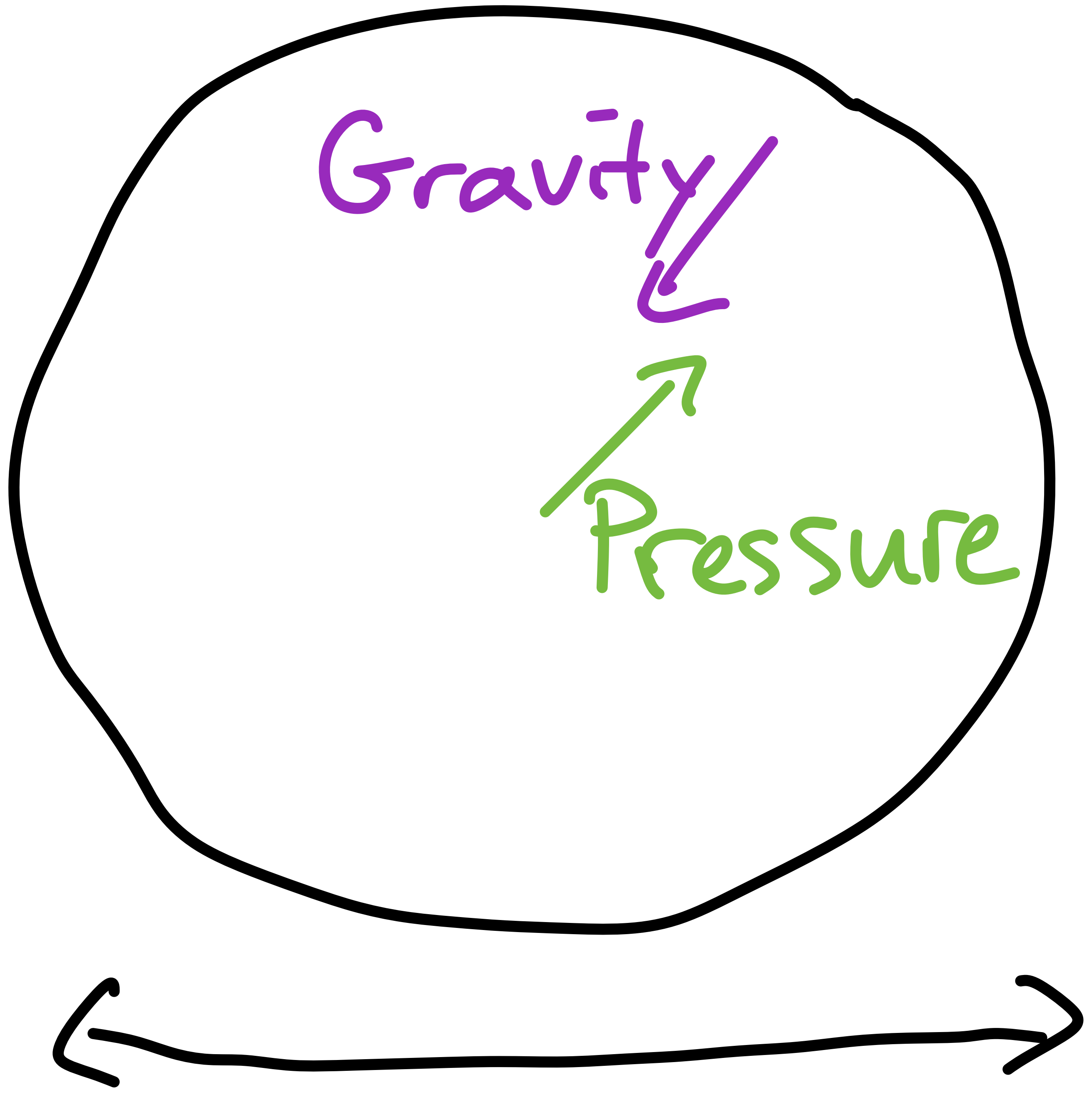
$M \sim M_{\odot} \sim 10^{57}\,\mathrm{GeV}$

TOV eq: $$\frac{dp}{dr} = -\frac{G\,\varepsilon(r)\,M(r)}{r^2} \times \underbrace{(GR)}_{\gtrsim 1}$$

E.o.S.: $p(r) = f[\varepsilon(r)]$



Neutron Stars

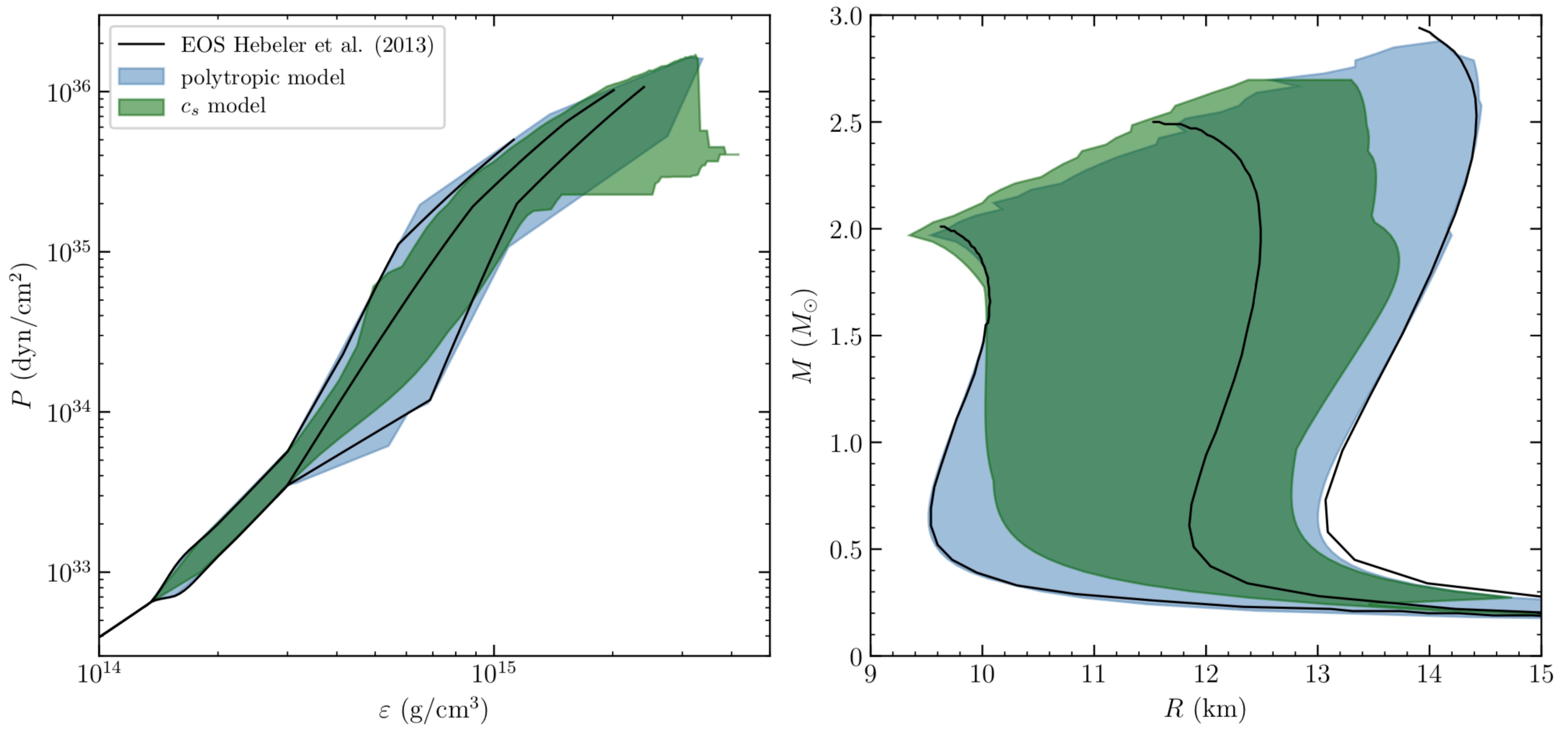


$\mathcal{O}(20\ \text{km})$

$M \sim M_\odot \sim 10^{57}\ \text{GeV}$

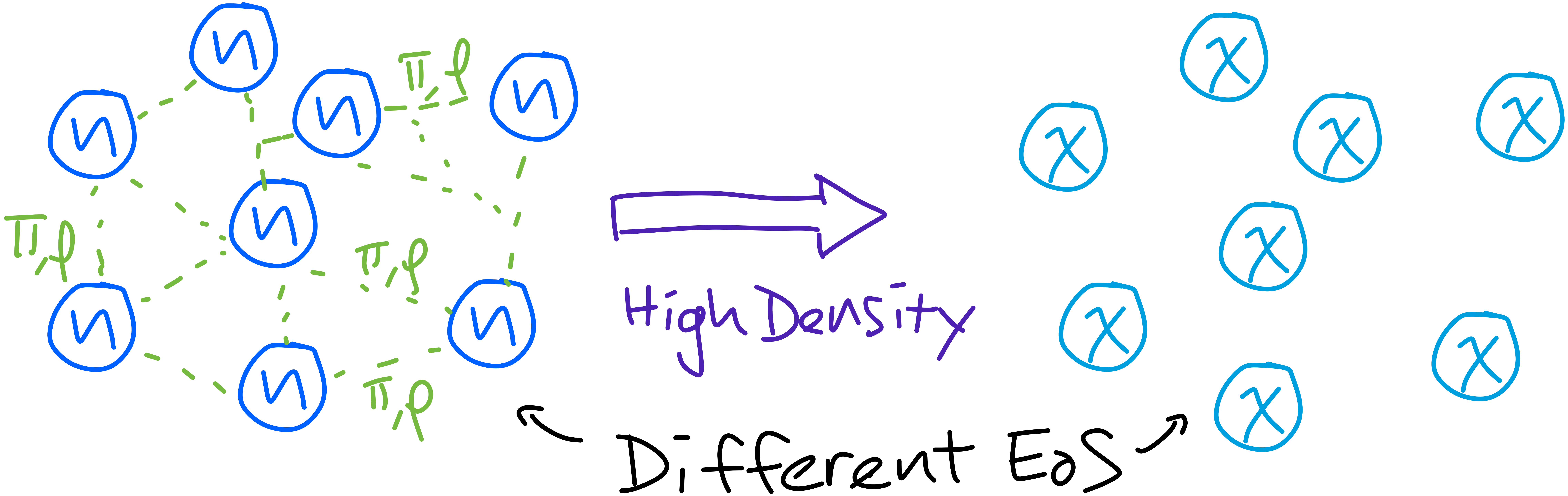
TOV eq: $\dfrac{dp}{dr} = -\dfrac{G\varepsilon(r)M(r)}{r^2} \times \underbrace{(GR)}_{\gtrsim 1}$

E.o.S.: $p(r) = f[\varepsilon(r)]$



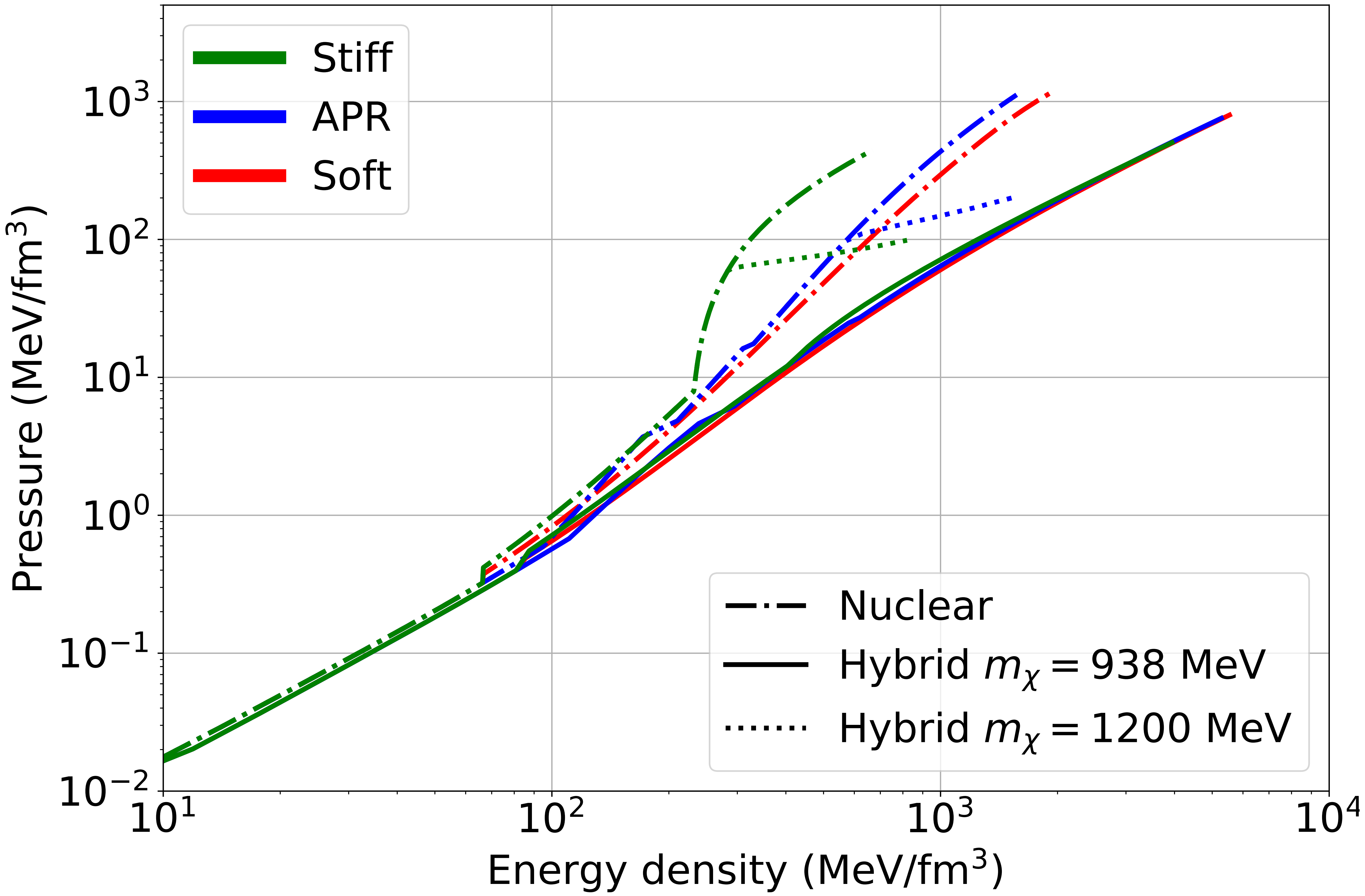
Greif, Raaijmakers, Hebeler, Schwenk, & Watts arXiv:1812.08188

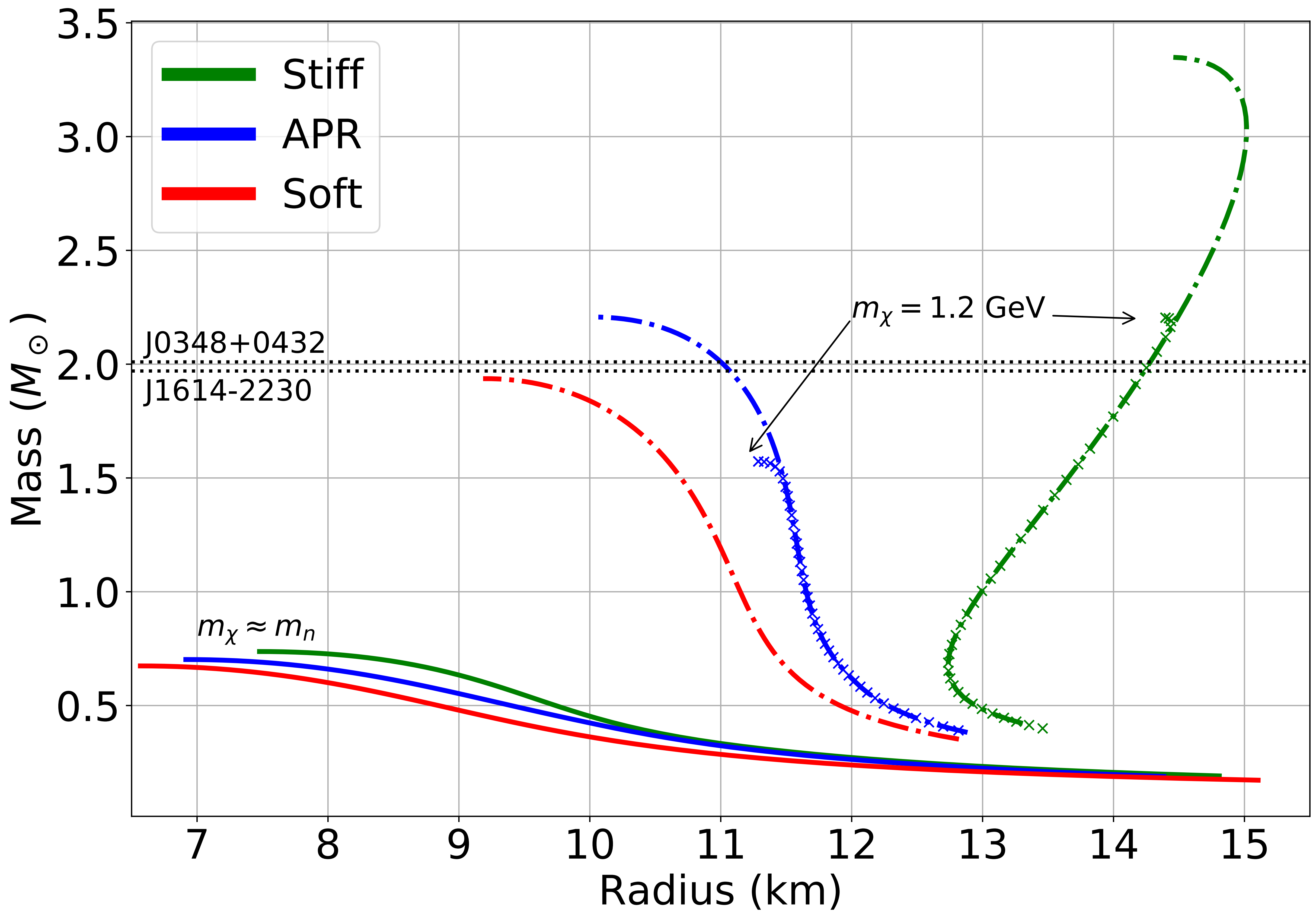
Neutron Stars & Dark Baryons



Neutron Stars & Dark Baryons

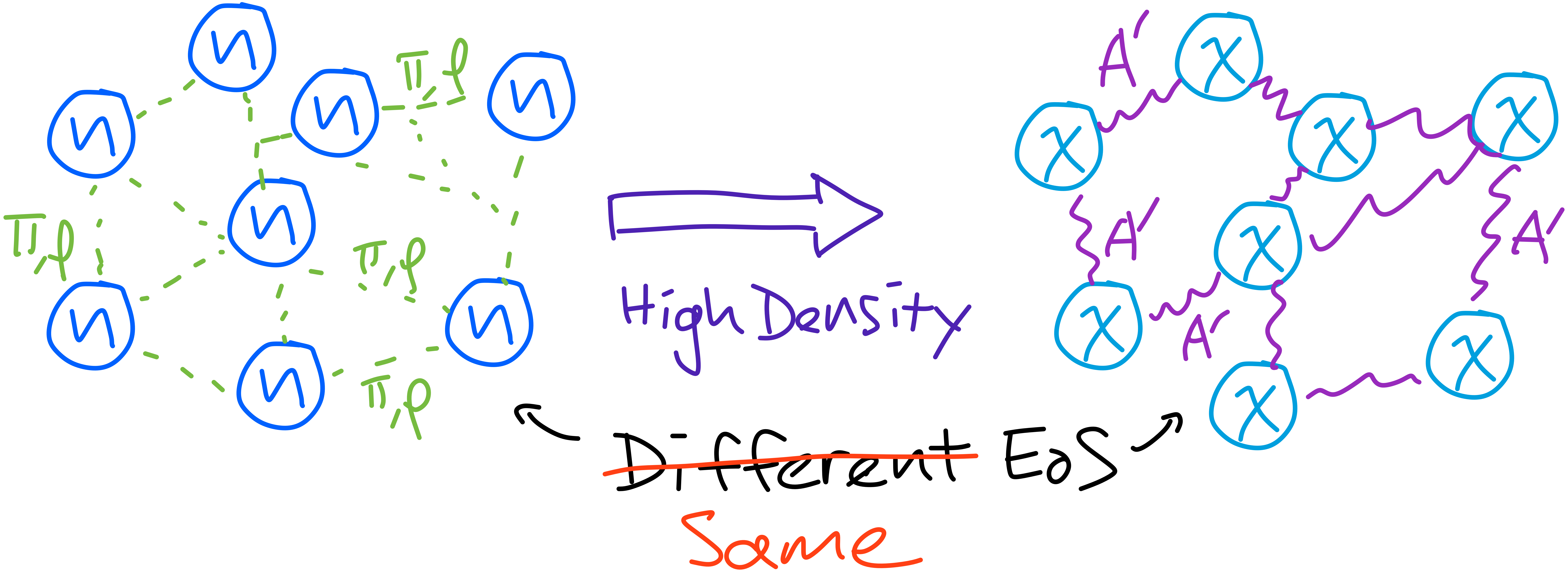
DM, Nelson, Reddy, & Zhou, PRL **121**, 061802; Baym *et al.*, Motta *et al.*, Mohapatra, Nussinov, *et al.*





Neutron Stars & Dark Baryons

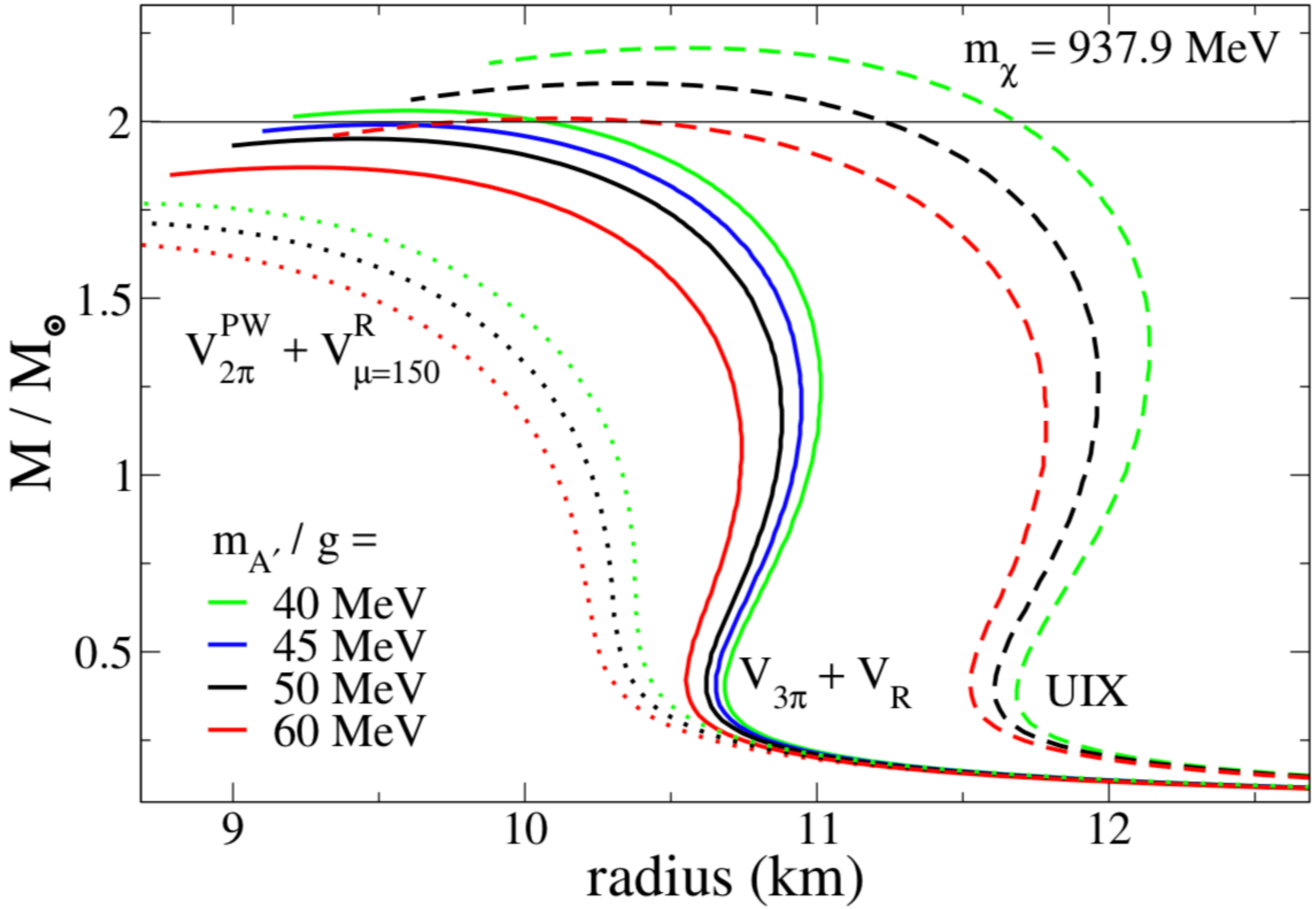
A way out?



Neutron Stars & Dark Baryons

A way out?

Cline & Cornell, JHEP **1807** 081



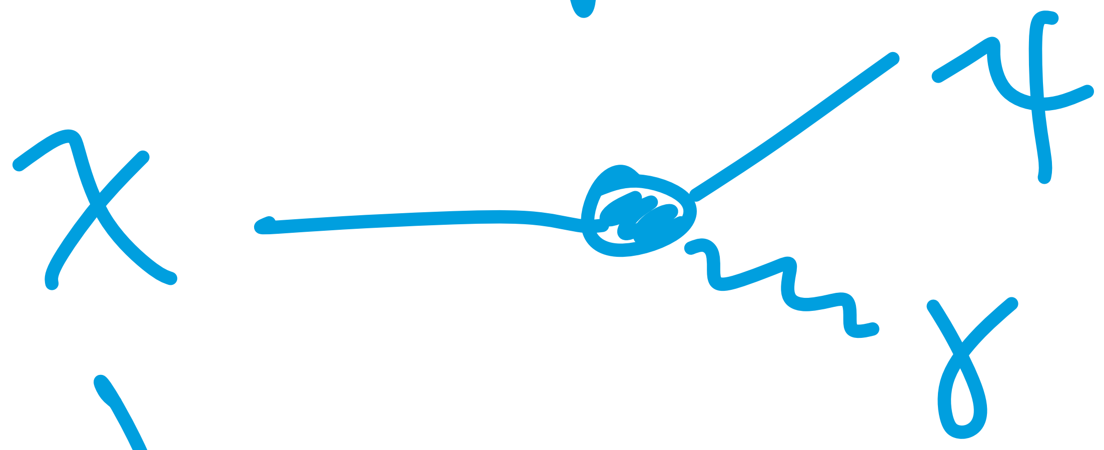
Exotic neutron decay invisible:

$n \to \chi A'$

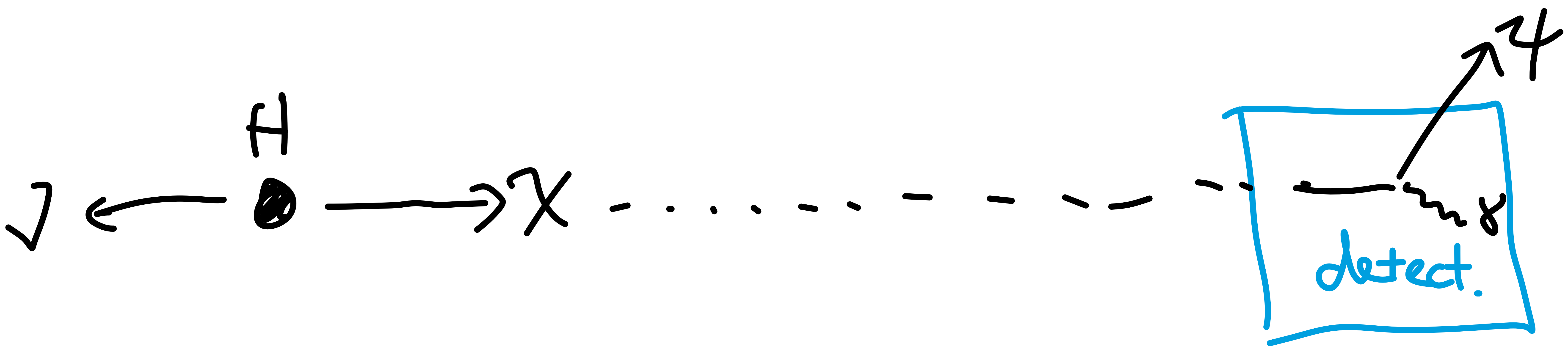
Other sources of dark baryons

Lots of H on Earth & in Sun!

Consider: χ has transition dipole to another dark baryon:



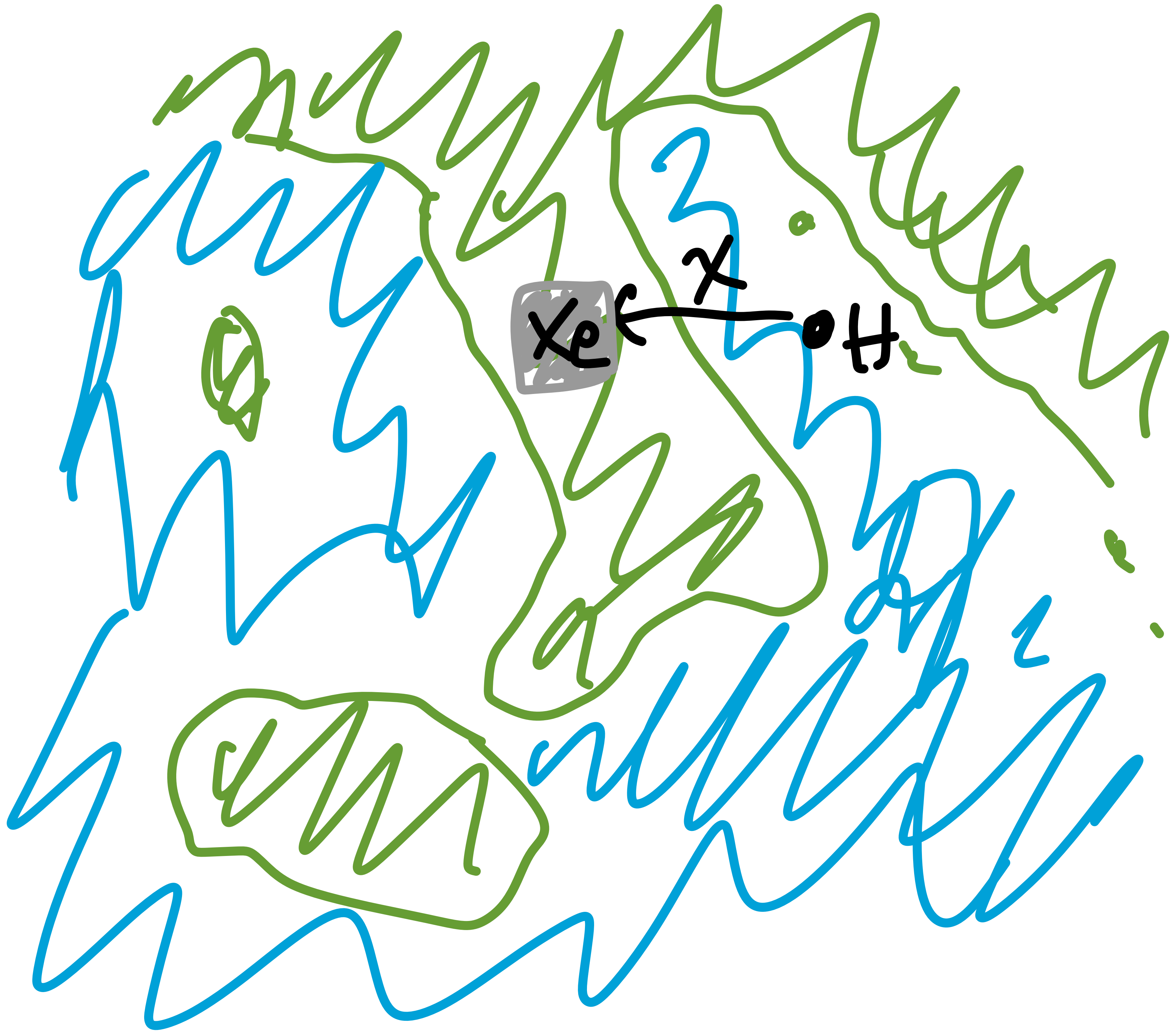
(NS $\Rightarrow$ nontrivial interactions)



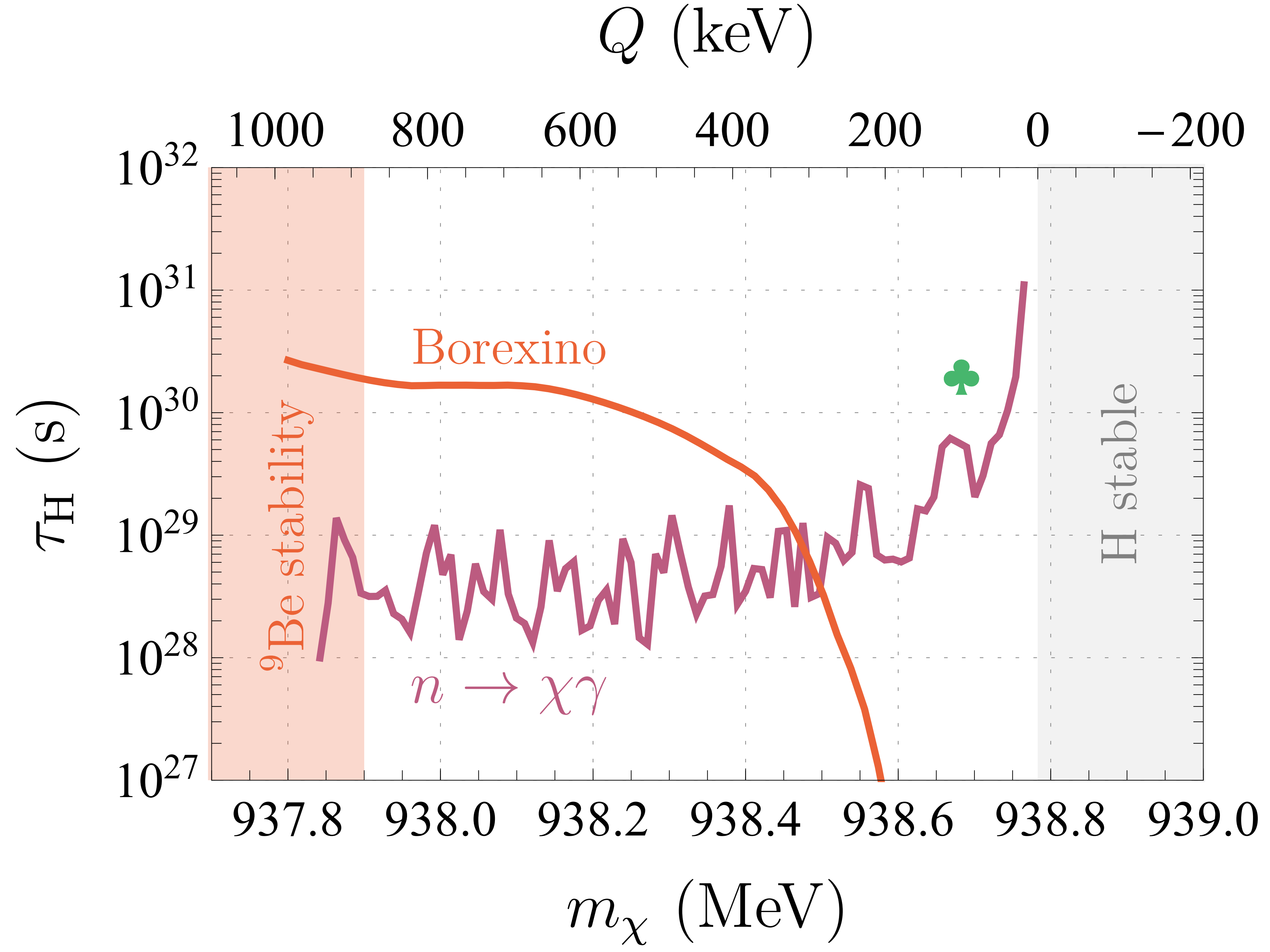
can see χ decay

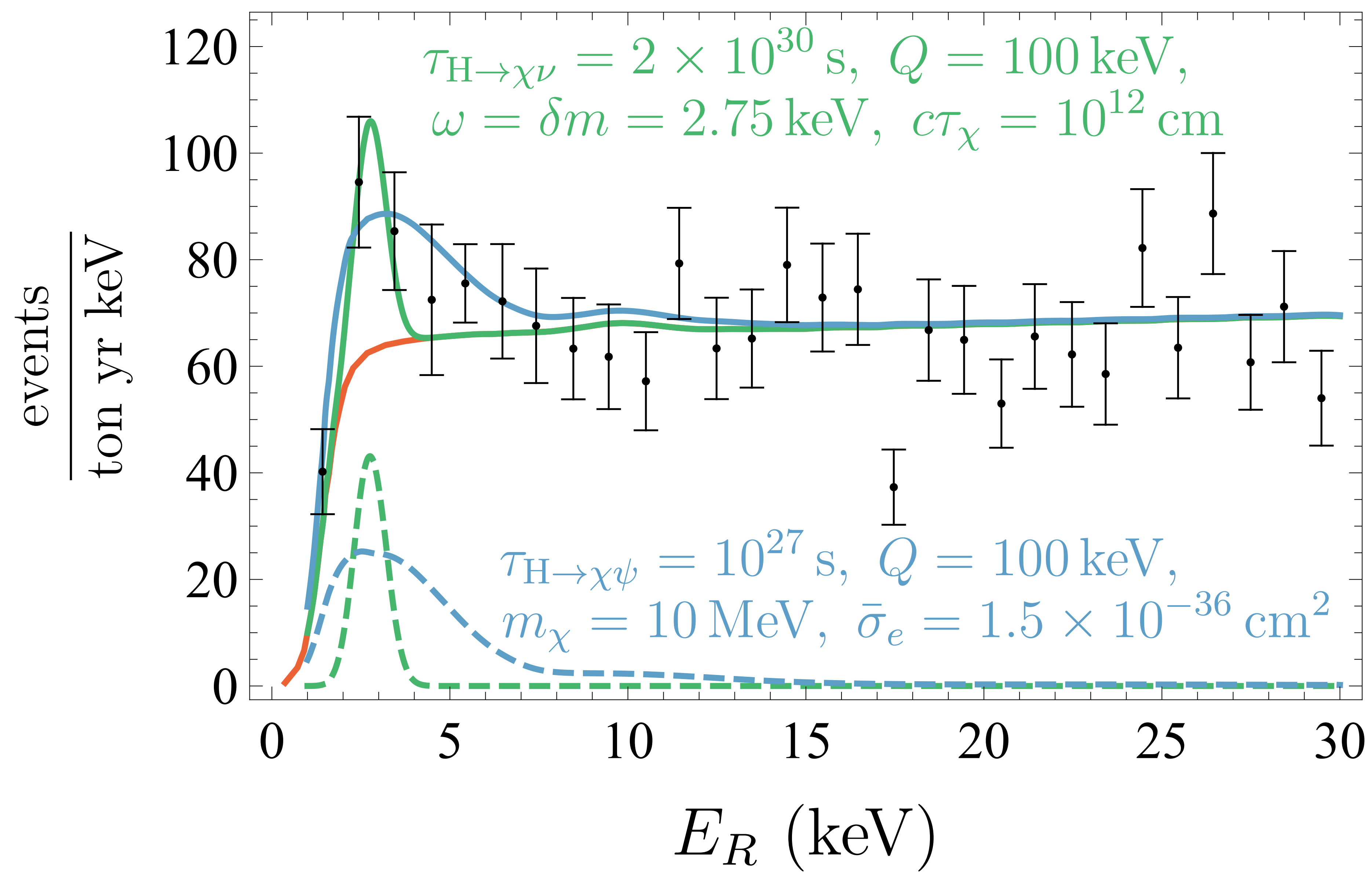
DM, Pospelov, Raj

Application: XENON1T



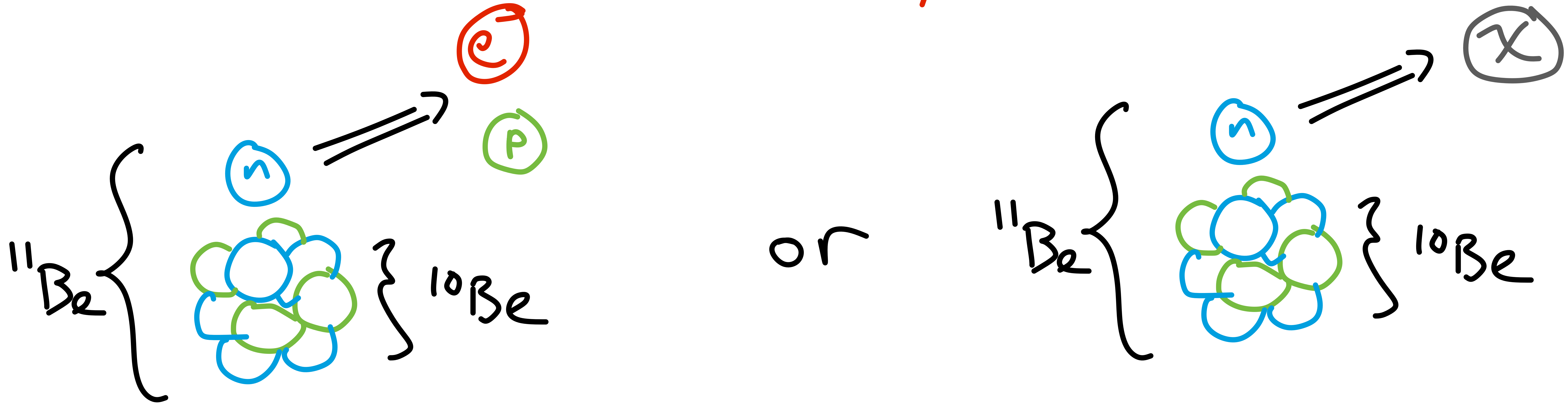
can fit recent excess in this setup





DM, Pospelov, Raj

Backup: ^{11}Be Decay



^{11}Be(βp), a quasi-free neutron decay?

K. Riisager[a,*], O. Forstner[b,c], M.J.G. Borge[d,e], J.A. Briz[e], M. Carmona-Gallardo[e],

^{11}B resonance?

Direct observation of proton emission in ^{11}Be

Y. Ayyad,[1,2,*] B. Olaizola,[3] W. Mittig,[2,4] G. Potel,[1] V. Zelevinsky,[1,2,4] M. Horoi,[5] S. Beceiro-Novo,[4]